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Research Article

Study on Rheological Characteristics of Uncemented Coal Gangue-Fly Ash Backfill (UCGFB) Slurry Based on Fractal Theory

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In order to explore the influence of gradation and concentration on the rheological parameters of uncemented coal gangue-fly ash backfill (UCGFB) slurry, based on the fractal theory, the particle size distribution of the mixture of coal gangue and fly ash under different mixing ratios are analyzed in this paper. On this basis, the influence of gradation and concentration on rheological parameters of UCGFB slurry are studied and a numerical simulation of slurry transportation is also carried out. The results show that (1) the fractal dimension can well characterize the grading characteristics of UCGFB mixtures, the larger the fractal dimension, the more fine particles in the material. (2) The fractal dimension of 2.628 is a critical point, when the fractal dimension of the mixture is greater than or equal to 2.628, the content of fine particles in the slurry can meet the requirements. On this basis, by adjusting the concentration of the slurry, the slurry can reach a good state. (3) When the slurry concentration reaches 79%, no matter how the gradation of the mixture changes, the rheological parameters of the slurry are at a high level. (4) In this paper, the average pressure loss per unit length pipeline is between 3000–8000 Pa for slurry with different mixing ratios, with a minimum value of 3070 Pa and the maximum value of 7697 Pa. Moreover, the pressure loss of bend is greater than that of straight pipe.

1. Introduction

Coal gangue is a kind of solid waste with a low calorific value produced in the process of coal mining and washing. According to statistics, by the end of 2019, China's accumulated amount of gangue has exceeded 6 billion tons, forming 1500–1700 gangue hills, covering an area of more than 200 thousand mu, the emission has increased by about 500–800 million t year by year [1]. Countries around the world have conducted a lot of exploration and practice on the comprehensive utilization of coal gangue, forming a comprehensive treatment and utilization system for power generation, road paving, production of building materials, production of chemical raw materials, agricultural application, and underground filling, but the comprehensive utilization rate of coal gangue is less than 30% [2–7]. The accumulation of coal gangue has brought great hidden dangers to the environment and personal safety. The main hazards caused are the occupation of land resources, pollution of groundwater, destruction of the soil environment, air pollution, and geological disasters [7, 8]. In order to realize the economic and efficient treatment of coal gangue, the UCGFB technology is slowly rising in China. The whole process is shown in Figure 1. The coal gangue is crushed to 3–6 mm, then according to the particle size distribution of the broken gangue, the appropriate proportion of fly ash is added, then water is added to mix to prepare a high-concentration slurry with a concentration of 76%–79%. The slurry is transported to the goaf through the filling pump and filling pipeline, which can not only achieve the purpose of economic and efficient treatment of the gangue but also play a certain supporting role on the roof of the goaf for reducing the ground surface subsidence [9–12].

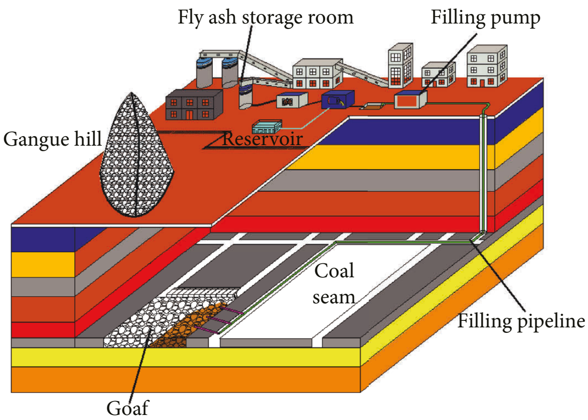


Figure 1: Schematic diagram of backfilling process.

The performance of filling slurry is very important to the transportation of slurry. The gradation of the materials is the key factor to determine the performance of the slurry, so it is necessary to study the influence of the gradation of the materials on the performance of the slurry [13, 14]. At present, the grading curve is often used to characterize the particle grading characteristics of materials, when grading parameters are directly used to evaluate the performance of filling slurry; it is difficult to establish a simple and clear evaluation relationship because there are several grading parameters. Therefore, it is of great significance to simply and quantitatively characterize the gradation of filling materials, then to evaluate the performance of filling slurry on this basis.

The fractal theory can quantitatively describe the complexity and space-filling capacity of geometric bodies and is suitable for characterizing the complex particle size distribution of mineral materials [15–19]. Many experts and scholars have applied it to rock mechanics, concrete, asphalt, and other fields and achieved certain results. Xu et al. [20] studied the fractal model of the particle size distribution of expansive soil, explained the physical mechanism of fractal particle size distribution, and obtained that the fractal dimension range of particle size distribution is between 2.0 and 3.0. Zhou [21] proposed a fractal model of rock-crushing particle size distribution, carried out ore-crushing tests, and pointed out that the fractal characteristics of ore are universal, and the fractal dimension, like other crushing indexes, can be used as an ideal index for evaluating crushing. Jiang et al. [22] combined fractal geometry with numerical simulation, used fractal dimension to characterize the distribution of rock joints, and studied its impact on the excavation of underground caverns. Hang and Yu [23] applied the fractal theory to the asphalt mixture, found that the asphalt mixture showed obvious fractal characteristics, and obtained the fractal dimensions of seven different gradations through calculation. Based on fractal theory, Chu et al. [24] obtained three algebraic expressions of fractal dimension, cumulative probability, and mass distribution of particles, which are functions of particle concentration, particle diameter, and maximum and minimum particle diameter. Konkol and Prokopski [25] measured the fractal dimension of the fracture surface of concrete containing variable kaolinite and speculated that the fracture toughness of this kind of concrete has a correlation with the fractal dimension. The Brazilian scholar Armandei and de Souza Sanchez Filho [26] took the fracture surface of steel fiber reinforced concrete as the research object, explored the relationship between the fractal dimension of the fracture surface, the content of steel fiber, and the concrete material, then based on this, discuss the material design scheme that can optimize the strength and fracture toughness.

Although the fractal theory has been applied to many fields, there is little research on the application of fractal theory to coal mine filling materials. Therefore, the purpose of this study is to analyze the gradation of filling materials based on fractal theory. Then on this basis, to study the influence of material gradation and concentration on the rheological properties of filling slurry.

2. Fractal Analysis of Material Gradation

2.1. Fractal Theory. According to the fractal theory, the number of particles passing through the sieve aperture r shall meet the formula (1), where D is the fractal dimension and r_{max} is the pore diameter of the screen when the particle passing rate is 100%.

$$N(r) = \left(\frac{r}{r_{max}}\right)^{-D}. \quad (1)$$

The number of particles in the interval $(r, r + dr)$ is

$$dN(r) = -Dr_{max}^{D} r^{-1-D} dr. \quad (2)$$

It is difficult to measure the number of particles passing through the sieve hole r during the experiment. In practice, the cumulative particle mass passing through the sieve hole r is used to represent the particle distribution. Assuming the density of particles isρ, the mass of particles in the interval $(r, r + dr)$ can be expressed as follows:

$$dM(r) = \rho V(r) dN(r) = -\rho k r^{3} D r_{max}^{D} r^{-1-D} dr, \quad (3)$$

where k is the particle volume factor based on the characteristic size, which is a constant.

The mass distribution function of particles is the following formula:

$$P(r) = \frac{M(r)}{M_0}, \quad (4)$$

where $P(r)$ is the mass distribution function of particles, which represents the passing rate of particles in the sieve hole r, and $M(r)$ is the mass of particles passing through the sieve hole r, that is the mass of particles (g) not larger than the particle size of r. M_0 is the total mass of particles, that is the mass of particles passing through the sieve aperture r_{max}. Formula (5) can be obtained by combining formulas (3) and (4).

$$P(r) = \frac{\rho k(-D) r_{max}^{D} r^{3-D}}{(3-D) M_0} + C. \quad (5)$$

$P(r_{max}) = 1$ and $P(r_{min}) = a$, which means that the ratio of particle mass is smaller than the minimum sieve aperture r_{min} to total mass is a. Formula (6) can be obtained by substituting the initial conditions into formula (5):

$$P(r) = \frac{(1-a)\left(r^{3-D} - r_{max}^{3-D}\right)}{r_{max}^{3-D} - r_{min}^{3-D}} + 1. \quad (6)$$

2.2. Calculation of Fractal Dimension of UCGFB Mixture. In this paper, the raw materials used to study the performance of UCGFB slurry are the gangue of the "Wangjiata" coal mine and the fly ash of the "Linxi" coal mine. The density of coal gangue is 2350 kg/m^3 and the density of fly ash is 2480 kg/m^3. The chemical composition of both is shown in Table 1. The particle size distribution of coal gangue (broken to 6 mm) and fly ash is shown in Figure 2. It can be seen from Figure 2 that compared with coal gangue, the content of fine particles in fly ash is more, and the proportion of particles below 200um is about 90%. The content of fine particles in coal gangue can be improved by adding fly ash to coal gangue. The particle size distribution of fly ash and coal gangue (crushed to 6 mm) mixed in different proportions are shown in Table 2.

The particle size distribution and fractal distribution fitting of the mixture after the fly ash and gangue are mixed in different proportions are shown in Figure 3. The fractal dimension and correlation coefficient are shown in Table 3, it can be seen from Table 3 that the fractal dimension of the mixture is different under different mixing ratios. With the increase of fly ash content, the content of fine particles in the mixture increases, and the fractal dimension becomes larger. The correlation coefficient R^2 of fractal distribution fitting mixture gradation is higher than 0.98, which indicates that fractal dimension D can well characterize the gradation characteristics of gangue and fly ash mixture.

3. Rheological Behavior Analysis Based on Fractal Theory

3.1. Test Scheme. Taking the coal gangue of the "Wangjiata" coal mine (crushed to 6 mm) and the fly ash of the "Linxi" coal mine as raw materials, the influence of gradation and slurry concentration on the rheological characteristics of slurry is studied. The research scheme is shown in Table 4. Four levels are set for each factor to conduct full factor tests, with a total of 16 groups of experiments.

3.2. Test Instrument. In this paper, the RheolaQC rheometer of Anton Paar Company in Germany is selected and connected to the computer through RS232. Figure 4 is the physical diagram of the RheolaQC rheometer. When testing the rheological properties of the UCGFB slurry, the shear test is carried out by controlling the shear rate. Put the rotor into a 500 ml beaker for the rheological test. Set the shear rate range to 0–150 s^{-1} and the time to 120 s through special software. The corresponding shear stress and viscosity are recorded in real time. In order to eliminate the error, the average value is obtained through multiple measurements.

3.3. Test Results and Analysis

3.3.1. Rheological Characteristic Index. Yield stress and viscosity are two basic parameters to characterize the rheology of slurry. The yield stress is the maximum shear stress that the slurry can bear when it only deforms without flowing under the action of external force, which reflects the initial cohesion of the slurry and is closely related to whether the slurry contains cementitious materials, additives, and the content of fine particles in the material. The viscosity reflects the internal friction of the slurry when it flows and is the macroscopic expression of the microscopic action of the fluid molecules. The viscosity of the slurry is related to the particle size, distribution, momentum exchange between the solid particles and the liquid molecules, and other factors.

3.3.2. Rheological Model. The concentration of the backfill slurry is as high as 76%–79%, which is in the form of paste. When the backfill slurry flows in the pipeline, the movement state is "plunger" moving as a whole. For high-concentration backfill slurry, the most commonly used rheological model is mainly the H-B model, and its rheological equation is expressed as

$$\tau = \tau_0 + \eta\left(\frac{\mathrm{du}}{\mathrm{dy}}\right)^n, \quad (7)$$

where τ is shear stress, Pa;du/dy is the shear rate, s^{-1};η is the viscosity, Pa·s;$\tau_0$is the yield stress; $n$is the rheological index, when $n = 1$, $\tau_0 = 0$, it is Newtonian fluid; when $n = 1$, $\tau_0 > 0$, it is Bingham body; when $n > 1$, it is an expansion body; when $n < 1$, it is pseudoplastic.

3.3.3. Experimental Result. The rheological data and fitting of the UCGFB slurry when the gradation $D = 2.658$ and the concentration are 76%, 77%, 78%, and 79%, respectively, is shown in Figure 5. It can be seen from Figure 5 that the relationship between the shear rate and shear stress of UCGFB slurry is an approximate straight line, which belongs to the characteristics of the Bingham body of non-Newtonian material. The rheological parameters of 16 groups of UCGFB slurry are shown in Table 5.

The change of rheological parameters of slurry along with fractal dimension under different concentrations is shown in Figure 6. It can be seen from the figure that when the fractal dimension is 2.512, the yield stress and viscosity of the slurry are the maximum values under the same concentration, indicating that the content of fine particles in the slurry is very low and the content of coarse particles is too much, and the relative motion between particles in the slurry is mainly sliding friction, the friction resistance between particles is large, as shown in Figure 7(a). When the fractal dimension increases from 2.512 to 2.599, the yield stress and viscosity of the slurry decrease rapidly, this is because the fine particles are equivalent to small balls, with

Table 1: Chemical composition of coal gangue and fly ash.

Chemical composition	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	K_2O	CaO	P_2O_5	SO_3
Gangue	50.6	23.9	7.7	1	2.3	5.1	0.1	8.1
Fly ash	52	29.3	9.83	2.03	3.63	2.34	0	0.89

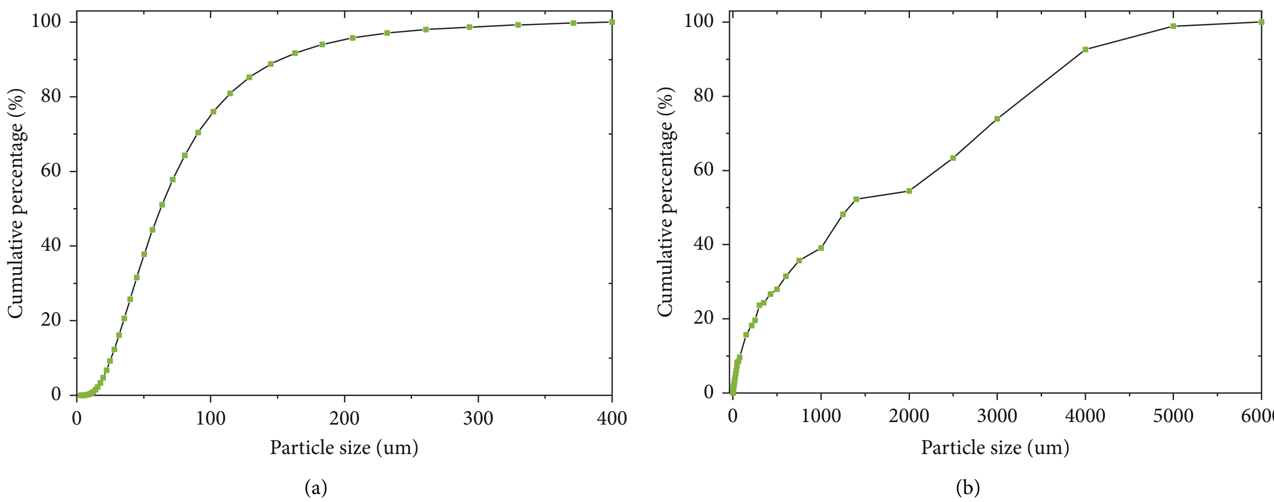


Figure 2: Cumulative distribution of particle size. (a) Fly ash. (b) Gangue.

Table 2: Particle size distribution of coal gangue and fly ash mixed in different proportions.

Particle size distribution (μm)	0 : 1	1 : 4	1 : 5.5	1 : 8	1 : 0
<5	1.61	1.22	1.29	1.35	0.02
<10	2.21	1.89	1.97	2.04	0.36
<25	4.18	5.19	4.95	4.74	4.77
<50	8.21	14.12	12.76	11.49	37.78
<75	9.64	19.92	17.55	15.35	61.00
<150	15.74	30.35	26.98	23.85	88.78
<300	23.70	38.71	35.24	32.04	98.72
<500	28.00	42.40	39.08	36.00	100.00
<1000	39.09	51.28	48.47	45.86	
<2000	54.46	63.57	61.47	59.53	
<3000	73.92	79.14	77.93	76.82	
<4000	92.58	94.07	93.73	93.41	
<5000	98.91	99.13	99.08	99.03	
<6000	100.00	100.00	100.00	100.00	

the increase of the content of fine particles in the slurry, part of the sliding friction between the coarse particles in the slurry changes to rolling friction, the rheological characteristics of the slurry will be improved to some extent, as shown in Figure 7(b). When the fractal dimension is increased from 2.599 to 2.628, the yield stress and viscosity of the slurry are further reduced, indicating that with the further increase of the content of fine particles in the slurry, the friction resistance between particles is further reduced, then the rheological property of the slurry is further improved.

When the fractal dimension is 2.628, the yield stress and viscosity of the slurry are at the lowest point under the same concentration. The yield stress and viscosity of the slurry with the concentration of 76% and 77% are basically the same, which indicates that the water content in the slurry with a fractal dimension of 2.628 and a concentration of 77% is an appropriate value, while the slurry with the fractal dimension of 2.628 and the concentration of 76% contains a small part of excess free water. When the fractal dimension increases from 2.628 to 2.658, the rheological parameters of the slurry with a concentration of 76% basically do not change, the yield stress and viscosity of the slurry with a concentration of 77%, 78%, and 79% gradually increase, and the larger the concentration, the greater the increase. The reason for this phenomenon is that when the fractal dimension is 2.628, the content of fine particles in the slurry has reached a sufficient or excessive state, and the coarse particles are suspended in the slurry and completely separated by the fine particles. The friction between particles is rolling friction, as shown in Figure 7(c). In this state, with the increase of fractal dimension, the content of fine particles in the slurry will further increase, but the friction between particles in the slurry will not decrease. For the slurry with the concentration of 77%, 78%, and 79%, the slurry concentration is high and the water content is low, when the concentration remains constant, the increase of the fine particle content will lead to the reduction of the thickness of the adsorption layer on the surface of the fine particles, which will lead to the reduction of the spacing between the particles. When the spacing between particles becomes smaller, the friction resistance between particles will become larger, which will lead to an increase in the yield stress and viscosity of the slurry. For the slurry with a concentration of 76%, the slurry contains a part of excess free water, which can meet the amount of water that needs to be adsorbed due to the increase of fine particles.

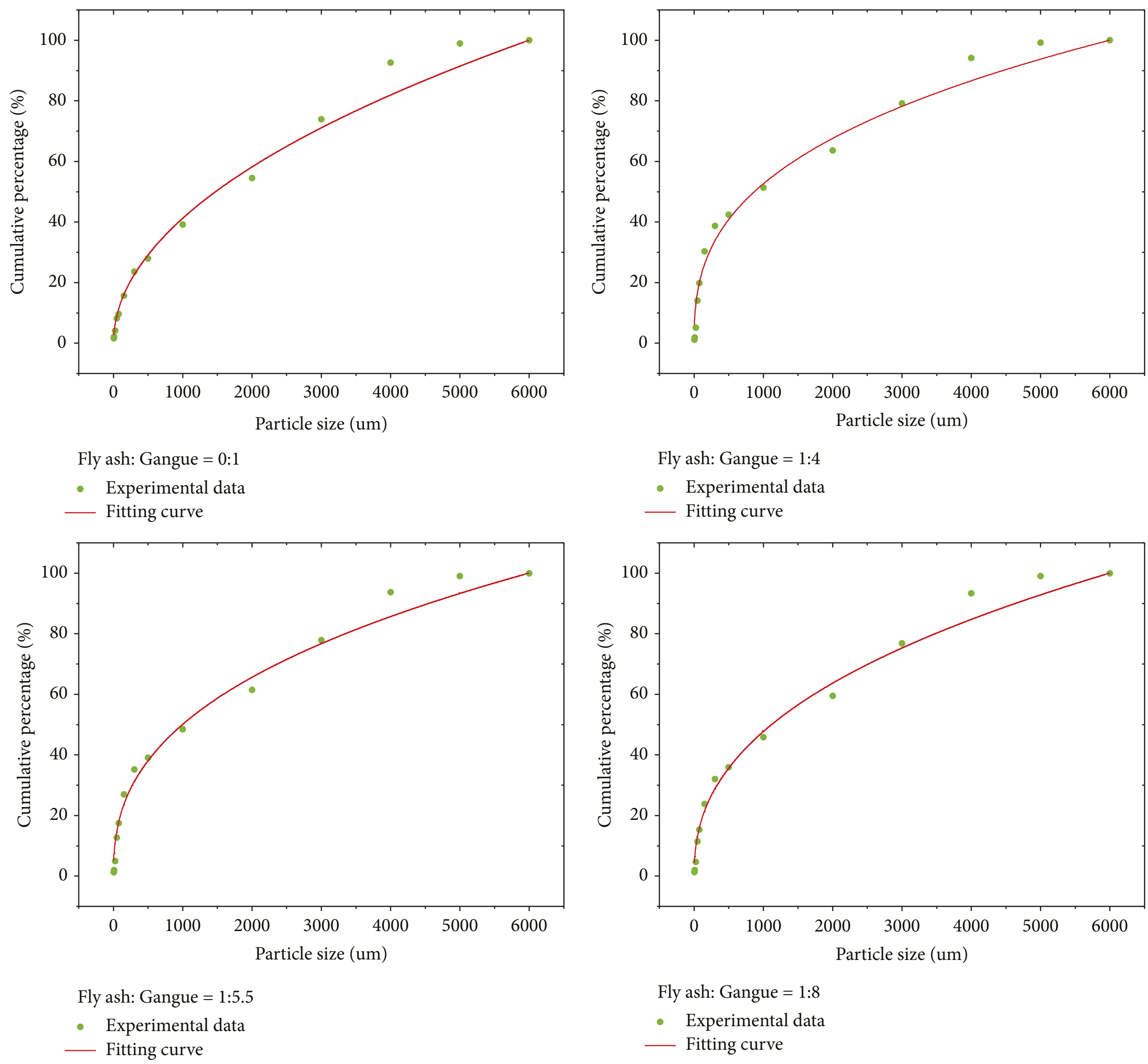


Figure 3: Particle size distribution and fitting of mixed materials.

Table 3: Fractal dimension and correlation coefficient.

Fly ash: coal gangue	Fractal dimension	Correlation coefficient R^2
0 : 1	2.512	0.989
1 : 4	2.658	0.984
1 : 5.5	2.628	0.987
1 : 8	2.599	0.988

Table 4: Test scheme.

Level	Factor		
	Grain gradation		Slurry concentration(%)
	Fly ash: coal gangue	Fractal dimension	
1	0 : 1	2.512	76
2	1 : 4	2.658	77
3	2 : 11	2.628	78
4	1 : 8	2.599	79

In addition, according to the fact that the yield stress and viscosity of the slurry with the fractal dimension of 2.628 and 2.658 are basically equal at the concentration of 76%, it can be concluded that the fractal dimension of 2.628 is a critical point, when the fractal dimension of particle gradation is greater than or equal to 2.628, the content of fine particles in the slurry is sufficient. This is because it is known from the previous analysis that the slurry with the fractal dimension of 2.628 and a concentration of 76% contains a part of excess free water, If the content of fine particles in the slurry with the fractal dimension of 2.628 is insufficient, when the fractal dimension changes from 2.628 to 2.658, the yield stress and viscosity of the slurry will inevitably be further reduced.

Figure 4: Rheometer.

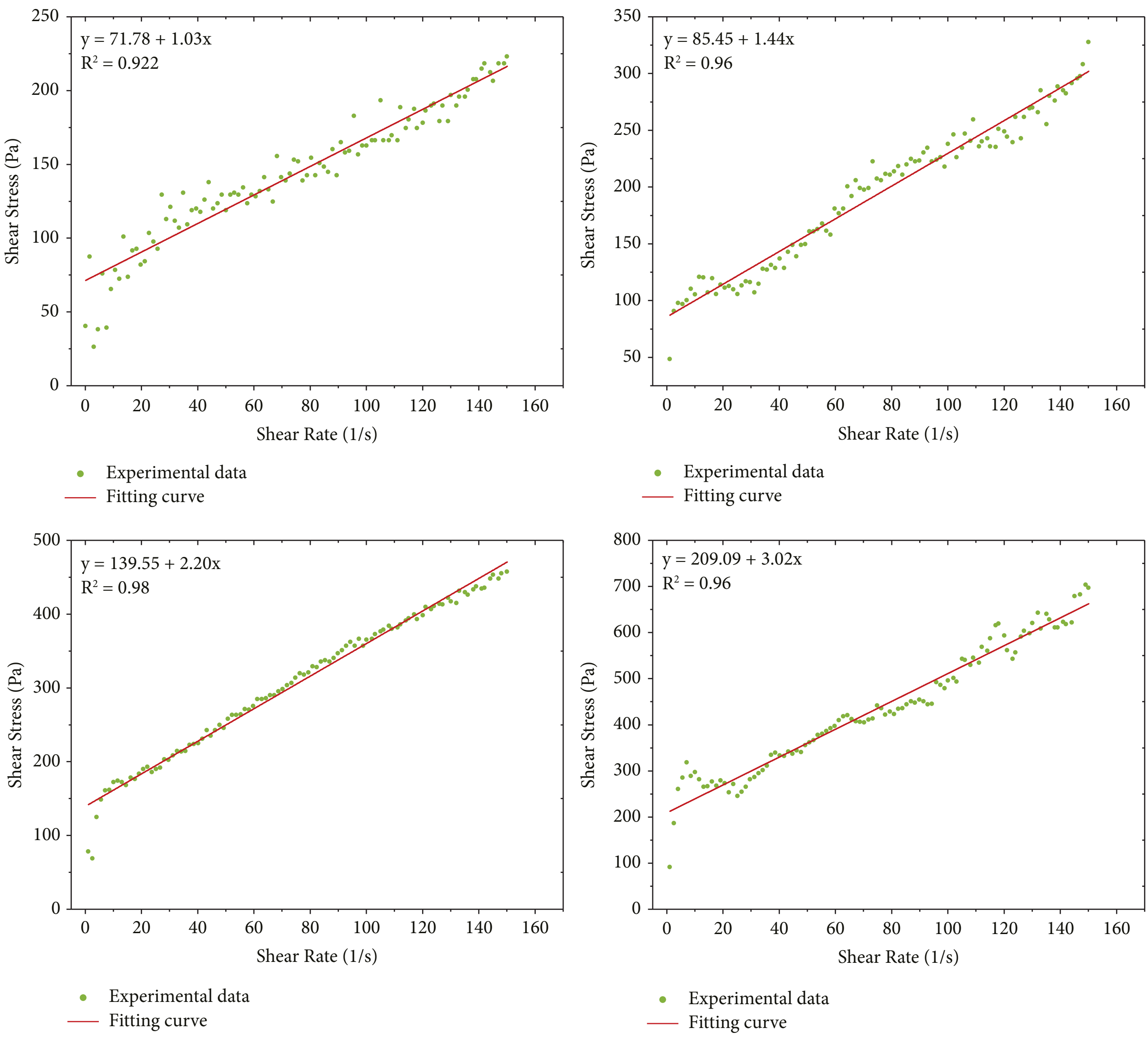


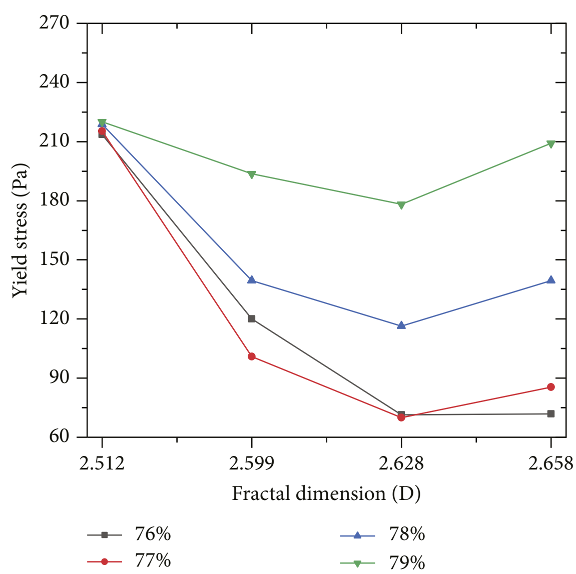
Figure 5: Rheological test results.

However, the test results show that there is no change in both, which indicates that the content of fine particles in the slurry has reached an appropriate content at this time.

The change of slurry rheological parameters with concentration under different fractal dimensions is shown in Figure 8. It can be seen from the figure that when the fractal

Table 5: Rheological parameters of slurry at different proportions.

Samples	Particle gradation: Fly ash: coal gangue	Particle gradation: Fractal dimension (D)	Slurry concentration (%)	Yield stress (Pa)	Dynamic viscosity (Pa·s)
1	1 : 4	2.658	76	71.78	1.03
2			77	85.45	1.44
3			78	139.55	2.20
4			79	209.09	3.02
5	2 : 11	2.628	76	71.30	1.04
6			77	70.00	1.05
7			78	116.36	1.74
8			79	178.18	2.43
9	1 : 8	2.599	76	120.07	1.49
10			77	100.91	1.42
11			78	139.55	2.04
12			79	193.64	2.63
13	0 : 1	2.512	76	213.65	2.77
14			77	215.36	3.00
15			78	218.78	3.32
16			79	220.00	3.42



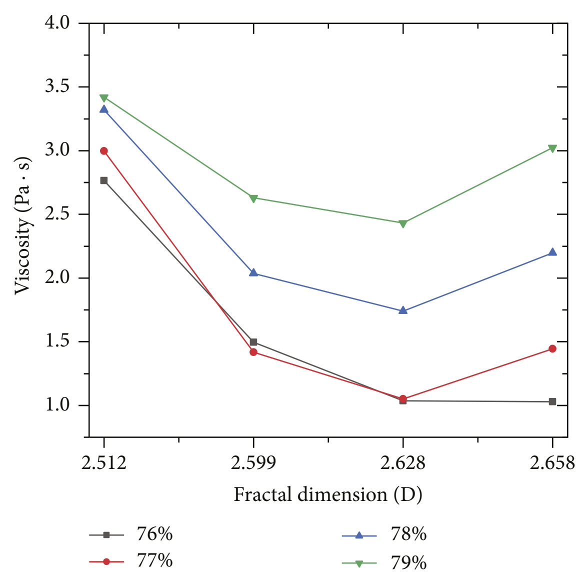
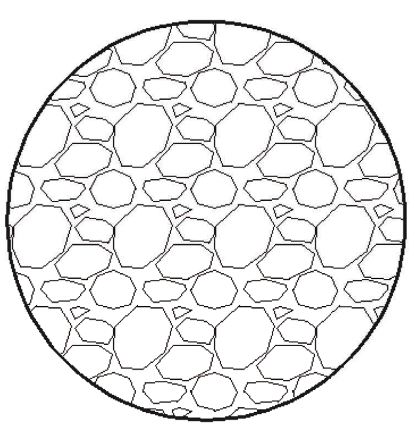
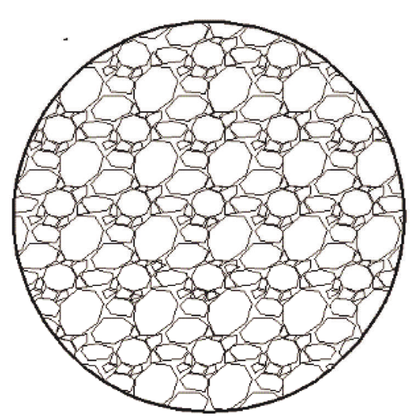


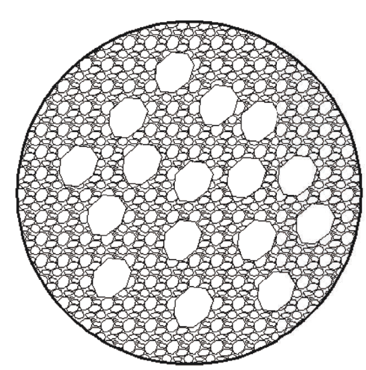
Figure 6: Effect of particle gradation on rheological parameters.



(a)



(b)



(c)

Figure 7: Stacking state of gangue particles.

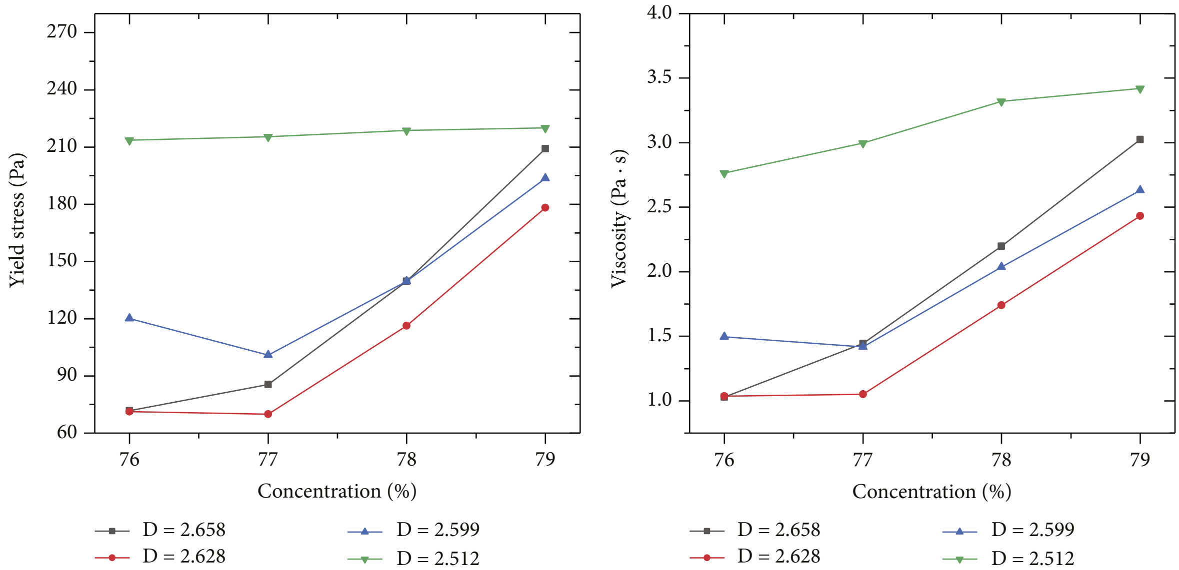


Figure 8: Effect of slurry concentration on rheological parameters.

dimension is 2.599, the yield stress and viscosity of the slurry will decrease as the slurry concentration increases from 76% to 77%, this is because the water content of the slurry with the fractal dimension of 2.599 and the concentration of 76% is too much, part of the free water could be secreted from the surface of the slurry, and some fine particles are suspended in the free water, which will cause the content of fine particles in the whole slurry system to decrease, the friction resistance between particles to increase, and the yield stress and viscosity of the slurry to increase. If the concentration of the slurry is increased, the bleeding amount of free water on the surface of the slurry can be reduced, which is equivalent to increasing the content of fine particles in the slurry system, so the yield stress and viscosity of the slurry will be reduced. When the fractal dimension is 2.628, as the slurry concentration increases from 76% to 77%, the yield stress and viscosity of the slurry remain basically unchanged, this is because at the concentration of 76%, the surface bleeding of the slurry is small, and the bleeding has little impact on the rheological parameters of the slurry, when the slurry concentration is increased to 77%, the bleeding amount on the slurry surface basically disappears, and the rheological property of the slurry basically does not change. When the fractal dimension is 2.658, as the slurry concentration increases from 76% to 77%, the yield stress and viscosity of the slurry gradually increase, the reason is that when the concentration is 76%, there is no redundant free water in the slurry, with the concentration increasing from 76% to 77%, the water content of the slurry is insufficient, resulting in the increase of the yield stress and viscosity of the slurry.

When the fractal dimension is 2.658, 2.628, or 2.599, the yield stress and viscosity of the slurry increase significantly with the slurry concentration increasing from 77% to 78% and then to 79%. The larger the fractal dimension, the faster the growth rate, which indicates that the larger the fractal dimension, the more sensitive the rheological parameters of slurry to the change of concentration. When the fractal dimension is 2.512, the yield stress and viscosity value of the slurry are at a very high level, and the change of the yield stress and viscosity value is very small with the change of the concentration, which indicates that when the content of fine particles in the slurry is too small, the rheological property of the slurry is very poor, and the rheological property of the slurry cannot be effectively improved only by adjusting the concentration of the slurry.

4. Numerical Simulation

4.1. Simulation Scheme. In this section simulation of the pipeline transportation of 16 different backfill slurry in Table 5 by ANSYS fluent soft will be conducted and the pipeline transportation resistance of backfill slurry will be analyzed. ICEM CFD is used to establish two models of straight pipe and elbow pipe (as shown in figure 9). The diameter of the pipeline is 0.2 m, the length of the straight pipe is 3 m, and the radius of curvature of the elbow is 0.6 m. In order to reduce the influence of the unstable transportation of slurry at the inlet and outlet due to the change of pipe diameter on the numerical simulation results, 1.6 m straight pipes are added at the inlet and outlet of the elbow. In order to facilitate the numerical simulation, the following assumptions are made in this paper: during the transportation process, the slurry is simplified as a single-phase flow, the filling slurry is incompressible and does not segregate, and has good integrity and uniformity. The solution settings are shown in Table 6.

4.2. Simulation Results and Analysis. Table 7 is a summary of the numerical simulation results of 16 kinds of slurries. Figure 10 is a numerical simulation cloud diagram of the

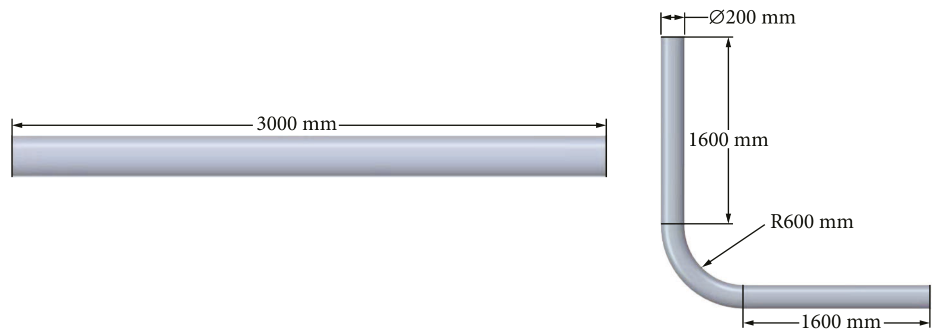


Figure 9: Pipeline model.

Table 6: Numerical simulation solution settings.

Model selection	Slurry density	Velocity-inlet	Pressure-out	Residual	Number of iterations
Viscous-laminar	1800 kg/m^3	1.5 m/s	$1 * 10^5$ Pa	0.001	500

Table 7: Summary of pressure loss per unit length of slurry with different proportions.

Particle grading (D)	Concentration (%)	Pressure loss per unit length (Pa)		
		Straight pipe	Bend	Mean value
2.658	76	3000	3139	3070
	77	3667	3863	3765
	78	5333	5311	5322
	79	7000	7243	7122
2.628	76	3000	3139	3070
	77	3000	3139	3070
	78	4333	4587	4460
	79	6000	6036	6018
2.599	76	4000	4346	4173
	77	3667	3863	3765
	78	5000	5070	5035
	79	6333	6519	6426
2.512	76	6667	6760	6714
	77	7000	7243	7122
	78	7667	7726	7697
	79	7667	7726	7697

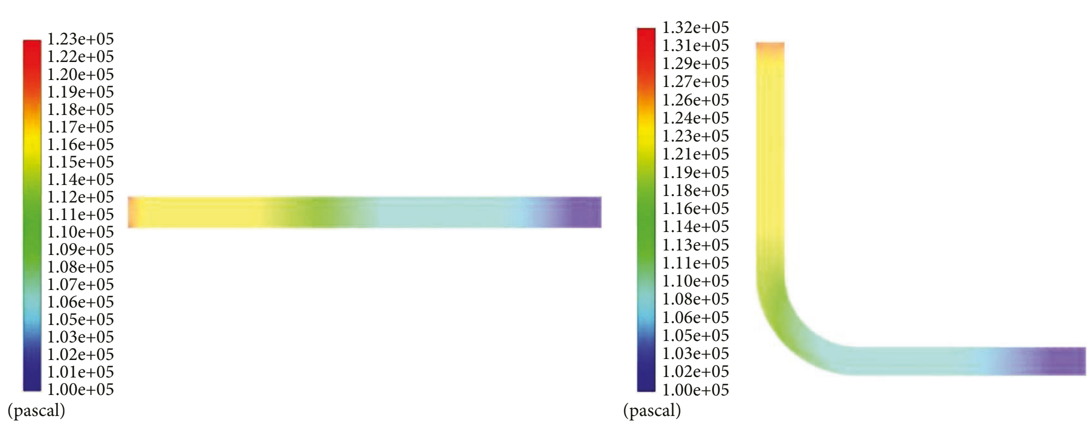


Figure 10: Numerical simulation diagram of slurry with a concentration of 79% and fractal dimension of 2.512.

backfill slurry with a concentration of 79% and a fractal dimension of 2.512. Figure 11 is a distribution diagram of the average pressure loss per unit length of the 16 kinds of slurries. It can be seen from the graph and table that (1) the average pressure loss per unit length pipeline of the slurry transported by the elbow and the straight pipe is between

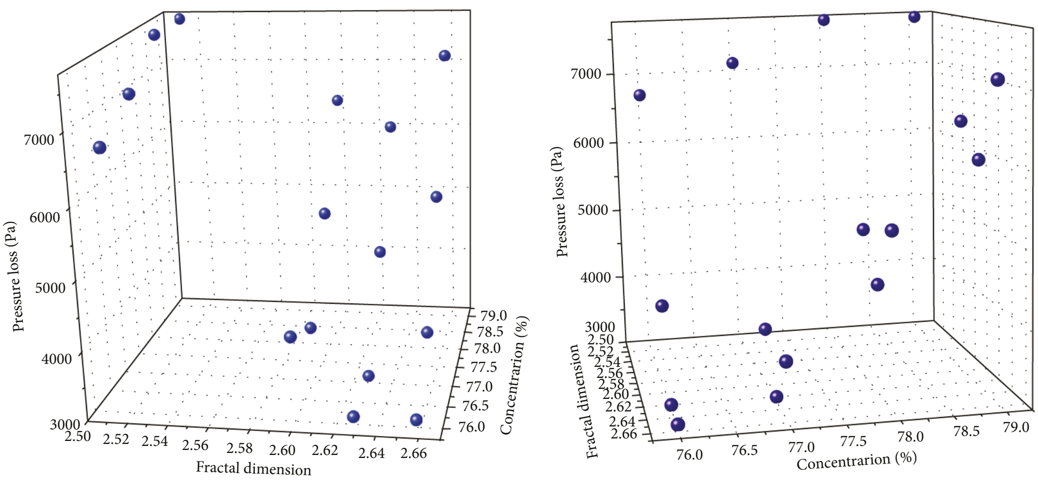


Figure 11: Average pressure loss per unit length of different slurries.

3000–8000 pa, the minimum value is 3070 Pa, the maximum value is 7697 Pa and the pressure loss of the elbow is greater than that of the straight pipe. (2) When the fractal dimension of the slurry gradation is 2.512, the pressure loss of the unit length of the pipeline is greater than 6000 Pa no matter what the slurry concentration is; when the slurry concentration is 79%, the pressure loss is greater than 6000 Pa regardless of the gradation, and the influence of gradation on the slurry performance is greater than the concentration. (3) When the fractal dimension $D \geq 2.599$ and the concentration $\leq$ 78%, the pressure loss per unit length of the pipeline is less than 5000 Pa.

5. Conclusion

(1) The fractal dimension can well characterize the gradation characteristics of the UCGFB mixture, and the larger the fractal dimension, the more fine particles in the material.

(2) The fractal dimension of 2.628 is a critical point. Only when the fractal dimension of the material is greater than or equal to 2.628, the content of fine particles in the slurry can meet the requirements. Based on this, by adjusting the concentration of the slurry, the UCGFB slurry can reach a good state.

(3) The average pressure loss per unit length pipeline of 16 kinds of backfill slurry is between 3000–8000 Pa, the minimum value is 3070 Pa, the maximum value is 7697 Pa, and the pressure loss of the elbow is greater than that of the straight pipe.

Data Availability

The data used to support the findings of this research are included within the paper.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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References

[1] L. J. Yu, Y. L. Feng, and W. Yan, "The current situation of comprehensive utilization of coal gangue in China," *Advanced Materials Research*, vol. 524-527, pp. 915–918, 2012.

[2] Y. Dong, X. Zhang, J. Lin, J. Zhao, and Z. Meng, "Experimental study on the compaction and deformation of filling gangue by reducing waste gangue for filling mining," *Frontiers in Materials*, vol. 8, Article ID 700118, 2021.

[3] B. Hao and C. Wang, "Influence on environment and comprehensive utilization measures of coal gangue," *Dynamics of Urban Agglomeration in China: Preferences of Energy-Saving and Environment-Friendly Society*, pp. 300–303, 2009.

[4] Y. Guo, C. Li, and M. Li, "Experimental study on cement stabilized macadam-gangue mixture in road base," *International Journal of Coal Preparation and Utilization*, vol. 42, no. 3, pp. 580–593, 2022.

[5] L. Li, G. Long, C. Bai, K. Ma, M. Wang, and S. Zhang, "Utilization of coal gangue aggregate for railway roadbed construction in practice," *Sustainability*, vol. 12, no. 11, p. 4583, 2020.

[6] Y. An, "Study on applicability of coal gangue at base layer of navigation airport pavement," *Materials Science, Energy Technology and Power Engineering III (MEP 2019)*, vol. 2154, Article ID 020014, 2019.

[7] T. Huang, S. M. Lei, Q. L. Ma, and E. W. Wang, "Progress of purification and applications of coal gangue," *Advanced Materials Research*, vol. 835-836, pp. 523–526, 2013.

[8] G. Hao, F. Yun, L. Zhanyuan, Y. Sen, and Z. Song, "Study on the property and reuse of coal gangue in Liupanshui, Guizhou Province, China," *International Journal of Mining, Reclamation and Environment*, vol. 27, no. 5, pp. 366–373, 2013.

[9] D. Wu, B. Yang, and Y. Liu, "Pressure drop in loop pipe flow of fresh cemented coal gangue–fly ash slurry: experiment and simulation," *Advanced Powder Technology*, vol. 26, no. 3, pp. 920–927, 2015.

[10] D. Wu, B. Yang, and Y. Liu, "Transportability and pressure drop of fresh cemented coal gangue-fly ash backfill (CGFB)

slurry in pipe loop," *Powder Technology*, vol. 284, pp. 218–224, 2015.
[11] D. Wu, T. Deng, and R. Zhao, "A coupled THMC modeling application of cemented coal gangue-fly ash backfill," *Construction and Building Materials*, vol. 158, pp. 326–336, 2018.
[12] D. Wu, Y. Hou, T. Deng, Y. Chen, and X. Zhao, "Thermal, hydraulic and mechanical performances of cemented coal gangue-fly ash backfill," *International Journal of Mineral Processing*, vol. 162, pp. 12–18, 2017.
[13] B. Yang, J. Jin, X. Yin, X. Wang, and H Yang, "Effect of concentration and suspension agent (HPMC) on properties of coal gangue and fly ash cemented filling material," *Shock and Vibration*, vol. 2021, Article ID 6643773, 12 pages, 2021.
[14] Y. Wang, Y. Huang, and Y. Hao, "Experimental study and application of rheological properties of coal gangue-fly ash backfill slurry," *Processes*, vol. 8, no. 3, p. 284, 2020.
[15] Y. Miao, "Rock fragmentation size distribution prediction and blasting parameter optimization based on the muck-pile model," *Mining, Metallurgy & Exploration*, 2021.
[16] Y. Xu, "Explanation of scaling phenomenon based on fractal fragmentation," *Mechanics Research Communications*, vol. 32, no. 2, pp. 209–220, 2005.
[17] J. A. Sanchidrián, F. Ouchterlony, P. Segarra, and P. Moser, "Size distribution functions for rock fragments," *International Journal of Rock Mechanics and Mining Sciences*, vol. 71, pp. 381–394, 2014.
[18] Y. Wang, W. Dan, Y. Xu, and Y. Xi, "Fractal and morphological characteristics of single marble particle crushing in uniaxial compression tests," *Advances in Materials Science and Engineering*, pp. 1–10, Article ID 537692, 2015.
[19] L. Rui Yang, "Rock unloading failure precursor based on acoustic emission parametric fractal characteristics," *Lithosphere*, 2022.
[20] Y. F. Xu, H. Matsuoka, and D. A. Sun, "Fractal model for grain-size distribution of soils," *Powders and Grains*, vol. 2001, 6 pages, 2001.
[21] H. P. Zhou, "Experiment study on crushing different ores based on fractal theory," *Manufacturing, Design Science and Information engineering*, vol. I AND II, pp. 591–598, 2015.
[22] Y. J. Jiang, Y. Tanabashi, B. Li, and J. Xiao, "Influence of geometrical distribution of rock joints on deformational behavior of underground opening," *Tunnelling and Underground Space Technology*, vol. 21, no. 5, pp. 485–491, 2006.
[23] J. B. Huang and X. Yu, "Relationship of high-temperature performance and aggregate gradation of asphalt mixtures based on fractal theory," *Applied Mechanics and Materials*, vol. 204-208, no. 1-5, pp. 3795–3798, 2012.
[24] H. Chu, F. Ren, Z. Zheng, and M. Gu, "Study on granularity distribution of powder by fractal models," *Fractals*, vol. 25, no. 4, Article ID 1740009, 2017.
[25] J. Konkol and G. Prokopski, "Fracture toughness and fracture surfaces morphology of metakaolinite-modified concrete," *Construction and Building Materials*, vol. 123, pp. 638–648, 2016.
[26] M. Armandei and E. de Souza Sanchez Filho, "Correlation between fracture roughness and material strength parameters in SFRCs using 2D image analysis," *Construction and Building Materials*, vol. 140, pp. 82–90, 2017.