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Article

Research on Cemented Paste Backfill Materials Based on the Crushing Efficiency of Coal Gangue from Bulianta Coal Mine

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Abstract: The storage of coal gangue, a solid waste byproduct, occupies valuable land resources and contributes to environmental pollution, making it a major concern. To enhance the utilization of coal gangue and promote its reduction at the source, resource recovery, and harmless disposal, this study investigates the preparation of cemented backfill materials using coal gangue from Bulianta Coal Mine as the binding agent. This approach aims to reduce the cost of cemented backfill. Three crushing methods were tested: two-stage crushing of coal gangue larger than 80mm, single-stage crushing of full-size coal gangue, and two-stage crushing of full-size coal gangue. The study involved crushing, screening, optimizing backfill proportions, and analyzing mechanical properties. Techniques such as X-ray diffraction (XRD) and X-ray fluorescence (XRF) were employed to support the research, yielding key performance indicators such as particle size distribution, uniaxial compressive strength, and bleeding rate. The results indicate that coal gangue particles were relatively coarse after single-stage crushing of full-size material, while the crushing method above 80mm yielded superior results. The particle size distribution post-crushing, with +4.75mm particles comprising 13.6%, was reasonable, and the resulting backfill slurry exhibited good workability. Among the three particle size combinations from the different crushing methods, the compressive strength of the backfill was significantly influenced. The highest compressive strength was achieved with two-stage crushing of coal gangue above 80mm, reaching 1.8 MPa at 7 days and nearly 4 MPa at 28 days. As the concentration increased, the coal gangue content rose, showing a positive correlation with strength.

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Coarse-grained coal gangue improved the bleeding properties of the backfill slurry, and as concentration increased and coal gangue content decreased, the bleeding rate gradually reduced.

Keywords: gangue; crushing; particle; grading; uniaxial compressive strength

1. Introduction

Coal gangue is a dark-gray rock with over 50% dry ash content, formed during coal mining and processing. As a solid waste byproduct of the coal industry, it is characterized by low carbon content and a harder texture than coal. Annually, the volume of coal gangue generated accounts for approximately 10% of the total coal production in that year. As the world's largest coal producer, China possesses vast quantities of coal gangue, which not only occupies large areas of land but also impacts the ecological environment. Additionally, the leachate from coal gangue can contaminate surrounding soil and groundwater. Under natural conditions, coal gangue can spontaneously combust, producing harmful gases such as CO, CO2, SO2, H2S, and NOx, with SO2 being the primary gas. Therefore, achieving the resource utilization of coal gangue is of significant importance.

China's efforts in the comprehensive utilization of coal gangue began in the 1950s and have accelerated since the "Ninth Five-Year Plan." The "Key Points of Technical Policy for the Comprehensive Utilization of Coal Gangue," issued in 1999, identified several main directions for coal gangue utilization, including power generation, building materials production, backfilling, and harmless treatment. These initiatives aimed to develop high-tech and high-value-added technologies and products. The "Guiding Opinions on the Comprehensive Utilization of Bulk Solid Wastes During the 14th Five-Year Plan Period," published in 2021, further outlined the direction for the comprehensive utilization of coal gangue and other bulk solid wastes.

Currently, the comprehensive utilization of coal gangue is widespread across China. In coal mining operations, coal and pyrite can be recovered from coal gangue. Additionally, it can be used for power generation as a low-calorific-value fuel, with its heat energy fully utilized through co-firing with washed coal. In the building materials sector, coal gangue can replace clay as a raw material for brick-making, cement production, ceramics, and as a lightweight aggregate for concrete. In engineering applications, coal gangue is used for road construction, land reclamation, and backfilling of gob areas and subsided zones. As an engineering filler, coal gangue is cost-effective and can be used in large quantities. Numerous studies have focused on the preparation of backfill slurries using coal gangue as a backfill aggregate, primarily analyzing the impact on the properties of the hardened slurry. However, there is limited research on the crushing characteristics of coal gangue itself and the study of its discharge gradation.

The northern Shaanxi region, rich in coal resources, features shallow coal seams with low ash, sulfur, and phosphorus content, and hosts significant coal gangue deposits. Locally, sand filling has become a major trend in the utilization of mine solid waste. As a filling aggregate, coal gangue must be crushed to meet specific particle size requirements. This study explores three crushing methods to determine the particle size distribution of crushed coal gangue. The mineral and chemical compositions of the coal gangue were analyzed using XRD and XRF methods to provide technical support for the experiment and to examine the various physical and mechanical properties of crushed coal gangue when applied in Cemented Paste Backfill Material (CPBM).

2. Materials and Methods

2.1 Analysis of Coal Gangue Characteristics

2.1.1 Particle Size Distribution of Coal Gangue

The coal gangue used in this experiment was sourced from the Bulianta Coal Mine. The test results for the particle size distribution of the raw coal gangue are presented in Table 1. The distribution is as follows: particles larger than 80mm account for 8.63%, particles between 80mm and 60mm make up 4.75%, and particles smaller than 60mm comprise 86.62%. Particle size is a crucial physical property of coal gangue, significantly influencing both the screening process and its resource utilization. Since the particle size of the incoming coal gangue did not meet the experimental requirements, a high-fineness crusher was employed to further reduce the size of the coal gangue.

Table 1. Raw coal gangue particle size distribution.

Particle size /mm	+80	-80~+60	-60
Volume /%	8.63	4.75	86.62

2.1.2 Chemical Composition of Coal Gangue

Coal gangue, a by-product of the coal-forming process, is found in various mining areas and stratigraphic layers. Due to differences in formation conditions and environments, the mineral composition of coal gangue can vary significantly. A comprehensive review of previous studies indicates that coal gangue is a mixture of several rock types, primarily including kaolinite, montmorillonite, quartz, pyrite, calcite, and other minerals. These minerals have two main sources: one originates from magmatic rocks formed by volcanic eruptions, which are subsequently weathered, transported, and deposited, such as quartz and feldspar; the other arises from chemical and biological processes in swamps, which form new minerals like calcite and pyrite. As an aggregate for paste backfill slurry, the chemical and mineral compositions of coal gangue are closely linked to the filling strength, water retention, and workability of the backfill slurry. Therefore, it is essential to analyze the chemical properties of coal gangue.

Table. 2 Chemical composition of coal gangue.

Element	Volume（wt%）	Element	Volume（wt%）
O	46	Mn	0.039
Si	28.26	V	0.015
Al	11.65	Sr	0.0141
Fe	3.117	Zr	0.0132
K	2.281	Cr	0.0117
Mg	0.86	Cl	0.011
Na	0.655	Zn	0.0091
Ca	0.608	Rb	0.0083
Ti	0.563	Cu	0.005
P	0.0645	Ni	0.005
Ba	0.0617	Ga	0.002
S	0.0534	As	0.001

According to Table 2, the coal gangue from Bulianta Coal Mine contains significant heavy metals that pose a potential risk to human health, with the following concentrations: Chromium (Cr) at 0.0117% and Arsenic (As) at 0.001%. Mercury (Hg), Lead (Pb), and Cadmium (Cd) were not detected. Based on the "Standard for Pollution Control on the Storage and Disposal of General Industrial Solid Wastes" (GB18599-2001), the heavy metal concentrations in the coal gangue from Bulianta Coal Mine are below the regulatory limits. With a pH value of 7, the coal gangue is classified as Class I general industrial solid waste.

2.1.3 Mineral Composition of Coal Gangue

As shown in the X-ray diffraction (XRD) analysis results in Figure 2, the coal gangue primarily consists of minerals such as kaolinite, quartz, albite, mica, chlorite, and microcline. Among these, kaolinite, quartz, mica, and albite are the most abundant in terms of mineral content.

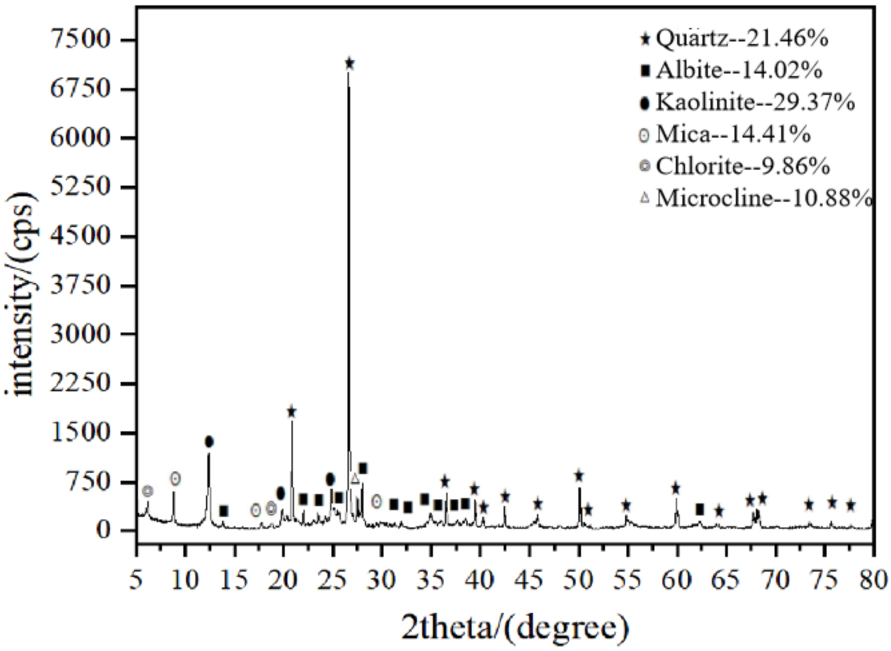

Figure. 1 XRD patterns of coal gangue

2.2 Methods

Using an industrial-grade double-stage crusher, the samples to be crushed include coal gangue samples ranging from 80 to 200 mm in size, as well as full-sized coal gangue samples. The crusher operates in two stages, with two sets of rotors arranged in series. In this design, materials crushed by the hammerheads of the upper rotor are immediately subjected to further fine crushing by the rapidly rotating hammerheads of the lower rotor. Inside the chamber, the materials collide rapidly in opposite directions, resulting in mutual crushing through both hammer-to-material and material-to-material impacts. This process optimizes the crushing outcome. The particle size distribution of the crushed materials is then measured, with the incoming coal gangue depicted in Figure 2.

Figure. 2 Incoming coal gangue

2.2.1 Experimental equipment

The experimental equipment required includes: a 2PC1416 double-stage industrial crusher, equipped with a set of standard stone sieve nets and a set of standard sand and gravel sieves (Figure 3); a curing box with temperature control set to 25°C ± 1°C and humidity maintained above 90%; and a universal pressure testing machine (model WDW-10) (Figure 4).

Figure 3. 2PC1416 double-stage industrial crusher

Figure 4. Universal pressure testing machine (model WDW-10)

2.2.2 Experimental procedure

Coal gangue particles larger than 80mm were manually sorted, and the selected coal gangue was fed into a 2PC1416 double-stage industrial crusher at a rate of 2.5 tons per minute for double-stage crushing. After crushing, the particle size distribution of the crushed coal gangue was measured using a standard sieve, with the process repeated four times. Next, a full-size range of coal gangue was poured into the same 2PC1416 crusher at the same rate for single-stage crushing. The particle size distribution after crushing was measured using a standard sieve, repeating the process four times. Finally, the full-size coal gangue underwent double-stage crushing again, and the particle size distribution was measured four times as before.

Through these three crushing schemes, the particle size distribution of the crushed coal gangue was obtained, and blending tests were conducted for each scheme. The cement dosages were 180 kg/m³, 220 kg/m³, 260 kg/m³, and 300 kg/m³, with fly ash proportions of 10% and 20% of the total gangue mass. Filling slurries with concentrations of 76%, 74%, and 72% were prepared by adjusting the amounts of water and gangue. After grouping and numbering, uniaxial compressive strength tests were conducted, and various properties of the slurries were investigated.

3. Results and discussion

3.1 Coal gangue crushing effect analysis

Particle size distribution reflects the relative content of each particle fraction and indicates the degree of integration among particles of different diameters. It is a key factor influencing the performance of filling materials to some extent[13]. A well-designed particle size distribution is essential for preparing high-quality cemented filling slurries. The particle size distribution data for the three different crushing methods are presented in Tables 3 to 5 below. The data reveal the following:

- For single-stage crushing of full-size range coal gangue, the proportion of particles larger than 4.75mm is 26.52%.
- For double-stage crushing of coal gangue larger than 80mm, the proportion of particles larger than 4.75mm is 13.6%.
- For double-stage crushing of full-size range coal gangue, the proportion of particles larger than 4.75mm is 4.01%.

After single-stage crushing of full-size range coal gangue, the crushed gangue tends to be relatively coarse, with larger particle sizes and lower crushing efficiency. In contrast, after double-stage crushing (whether of coal gangue larger than 80mm or full-size range coal gangue), the particle sizes are more consistent. Additionally, both the single-stage crushing of full-size range coal gangue and the double-stage crushing of coal gangue larger than 80mm result in a small proportion of particles larger than 16mm, indicating the presence of larger particles.

Table 3. Testing results of particle size distribution after single-stage crushing of full-size range coal gangue.

Particle size (mm)	Volume (%)	Particle size (mm)	Volume (%)
+16	1.85	+16	1.85

-16~+9.5	6.15	+9.5	8.00
-9.5~+4.75	18.52	+4.75	26.52
-4.75~+2.36	20.25	+2.36	46.77
-2.36~+1.18	12.67	+1.18	59.44
-1.18~+0.6	12.87	+0.6	72.31
-0.6~+0.3	12.5	+0.3	84.81
-0.3~+0.15	9.85	+0.15	94.66
-0.15	5.34	-0.15	5.34

Table 4. Testing results of particle size distribution after double-stage crushing of coal gangue larger than 80mm**.**

Particle size (mm)	**Volume (%)**	**Particle size (mm)**	**Volume (%)**
+16	0.32	+16	0.32
-16~+9.5	2.97	+9.5	3.29
-9.5~+4.75	10.49	+4.75	13.78
-4.75~+2.36	14.46	+2.36	28.24
-2.36~+1.18	14.59	+1.18	42.82
-1.18~+0.6	27.28	+0.6	70.11
-0.6~+0.3	12.46	+0.3	82.57
-0.3~+0.15	14.23	+0.15	96.8
-0.15	3.2	-0.15	3.20

Table 5. Testing results of particle size distribution after double-stage crushing of full-size range coal gangue.

Particle size (mm)	**Volume (%)**	**Particle size (mm)**	**Volume (%)**
+16	0	+16	0
-16~+9.5	0.71	+9.5	0.71
-9.5~+4.75	3.3	+4.75	4.01

-4.75~+2.36	13.08	+2.36	17.09
-2.36~+1.18	12.55	+1.18	29.64
-1.18~+0.6	16.58	+0.6	46.22
-0.6~+0.3	16.42	+0.3	62.64
-0.3~+0.15	14.7	+0.15	77.34
-0.15	22.66	-0.15	22.66

Based on the data presented in the table, Figure 5 illustrates the particle size distribution curves for coal gangue processed using three different crushing methods. Notably, the curve for full-size range double-stage crushing after four passes shows a smooth and continuous distribution, while the curve for full-size range single-stage crushing is less continuous. The gradual crushing of cleavage planes and joints in coal gangue results in finer coal particles and coarser rock particles due to the hardness of the rock[14].

The grading distribution curve for full-size range double-stage crushing has a steeper slope, indicating a narrower particle size range and poorer grading. In contrast, the curves for the crushing of coal gangue larger than 80mm and the full-size range single-stage crushing exhibit gentler slopes, suggesting better grading. This better grading allows finer particles to fill the voids of coarser particles, thereby reducing the void ratio and creating a denser backfill structure.

The fineness modulus, an important indicator of the quality of coal gangue crushing, directly affects the workability and compressive strength of the backfill slurry. As shown in Table 6, full-size range single-stage crushing yields the highest fineness modulus, followed by the crushing of coal gangue larger than 80mm, and then full-size range double-stage crushing. A higher fineness modulus signifies a larger proportion of coarse particles, which can result in poor water retention and an increased likelihood of bleeding and segregation in the slurry.

Considering both particle size distribution and fineness modulus, the crushing method using coal gangue larger than 80mm is deemed the most effective. This method produces a backfill slurry with excellent workability and enhances the strength of the hardened backfill material.

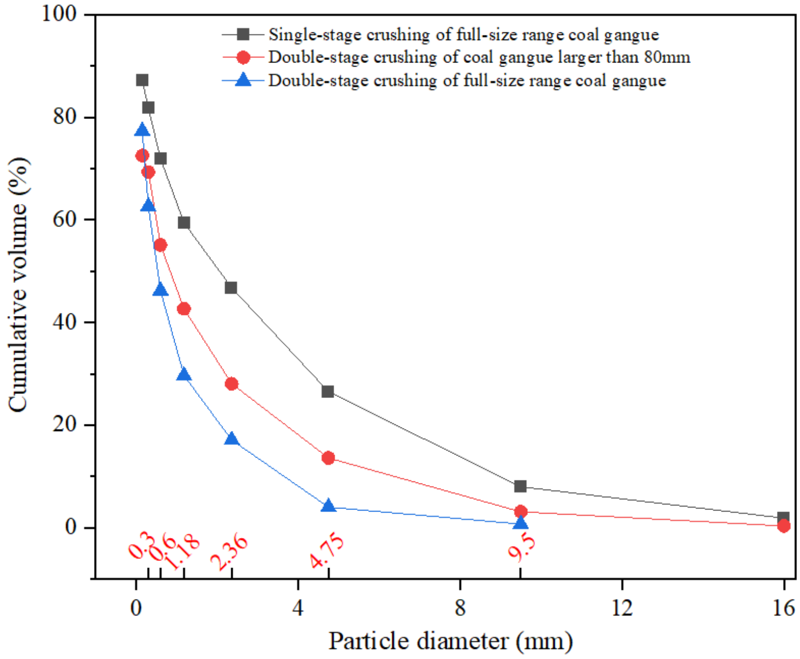

Figure 5. Particle gradation curve.

Table 6. Fineness modulus of crushed coal gangue.

Crushing method	double-stage crushing of coal gangue larger than 80mm	single-stage crushing of full-size range coal gangue	double-stage crushing of full-size range coal gangue
Fineness modulus	2.83	3.70	2.34

3.2 Uniaxial compressive strength

The selection and optimization of backfill materials significantly impact the physical and mechanical properties of the backfill bodies in underground working faces and gob areas, effectively controlling surface subsidence and collapses. As a cementitious material, coal gangue can replace a portion of cement, thereby increasing the utilization of gangue solid waste and enabling the replacement of coal with gangue, thus eliminating the need to transport gangue to the surface. This backfill material proportioning experiment combines coal gangue, fly ash, cement, and water in different proportions to investigate the consolidation characteristics and strength indicators of cemented specimens with various coal gangue particle sizes under three crushing schemes. The objective is to assess whether the backfill bodies meet the mining strength and related process requirements. After the specimens have been cured for the specified period, their uniaxial compressive strengths are measured, with the data presented in Tables 7 to 9.

Table 7. Proportioning test for double-stage crushing of coal gangue larger than 80mm.

Number	Concentration (%)	Dosage per cubic meter (t/m^3)				Strength（MPa）		
		Cement	Coal gangue	Fly ash	Water	7d	14d	28d
1	76	0.18	1.012	0.202	0.440	1.807	2.962	3.908
2	74	0.18	0.958	0.192	0.467	1.445	2.508	3.884
3	72	0.18	0.906	0.181	0.493	1.263	2.112	2.529

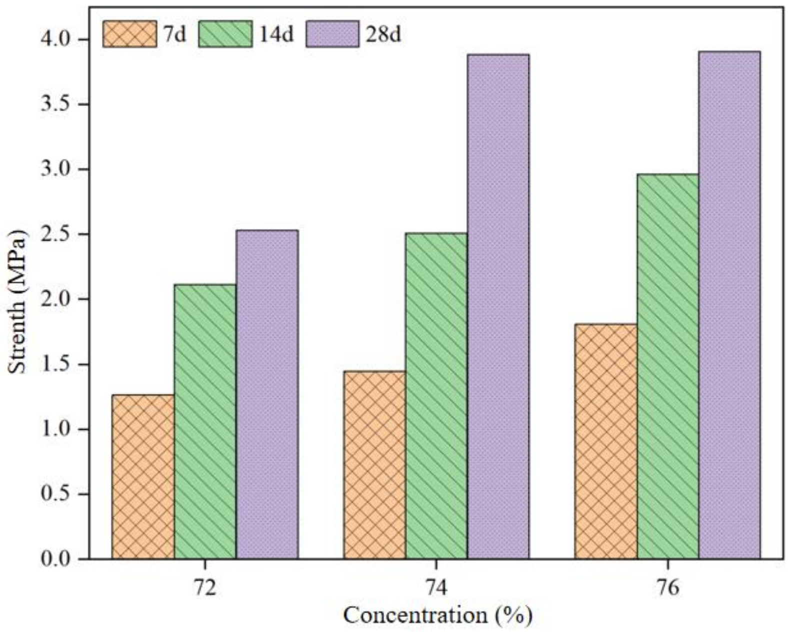

Figure 6. Strength of backfill made of double-stage crushed coal gangue larger than 80mm**.**

Table 8. Proportioning tests for double-stage crushed full-size range coal gangue**.**

Number	Concentration (%)	Dosage per cubic meter (t/m^3)				Strength（MPa）		
		Cement	Coal gangue	Fly ash	Water	7d	14d	28d
1	76	0.18	1.120	0.112	0.446	1.162	2.133	2.452
2	74	0.18	1.059	0.106	0.473	0.842	1.386	2.126
3	72	0.18	1.001	0.100	0.498	0.541	1.046	1.689

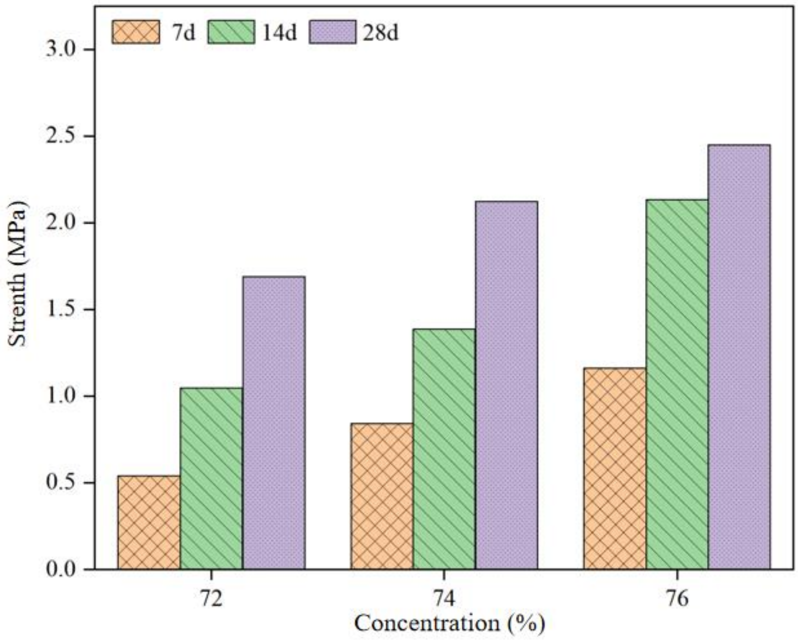

Figure 7. Strength curve of full-size range material after double-stage crushing**.**

Table 9. Proportioning test of full-size range coal gangue after single-stage crushing**.**

Number	Concentration (%)	Dosage per cubic meter (t/m^3)				Strength（MPa）		
		Cement	Coal gangue	Fly ash	Water	7d	14d	28d
1	76	0.18	1.012	0.202	0.440	1.252	2.488	3.608
2	74	0.18	0.958	0.192	0.467	1.127	2.107	2.807
3	72	0.18	0.906	0.181	0.493	0.795	1.422	2.249

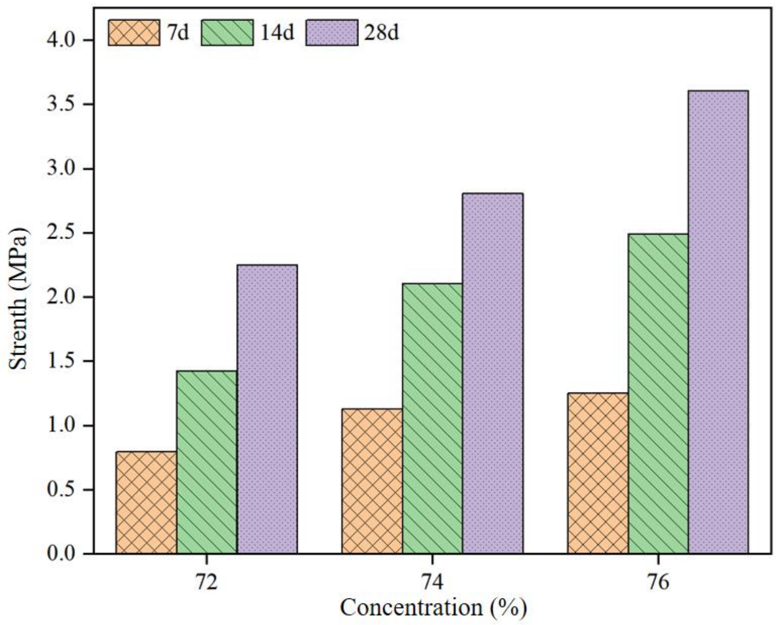

Figure 8. Strength Curve of Full-Size Range Material after Single-Stage Crushing

As depicted in the graph, the compressive strength of the backfill is notably influenced by the particle size distribution resulting from three distinct crushing methods. As the concentration of coal gangue increases, a positive correlation trend in strength emerges. Notably, the backfill composed of coal gangue crushed in two stages, with particle sizes exceeding 80mm, exhibits the highest compressive strength, reaching 1.8 MPa at 7 days and nearly 4 MPa at 28 days. The initial strengths of backfills made from full-size range coal gangue after both single-stage and double-stage crushing are comparable. In contrast, the early strength of the backfill incorporating coal gangue crushed to particle sizes larger than 80mm is nearly twice that of the other two crushing methods. This underscores the enhancement in strength provided by coarse aggregates in coal gangue, showcasing a micro-aggregate effect [4, 15]. Consequently, coarse-grained coal gangue significantly impacts the early strength of the backfill.

Furthermore, considering the chemical composition analysis and XRD mineral composition, the high proportions of silicon oxide, alumina, and other components in coal gangue expedite the hydration reaction, generating more hydrated products like C-S-H gel and Aft. Simultaneously, coarse-grained coal gangue fills the pores, fostering a more stable structure and resulting in a denser backfill with reduced porosity.

Maintaining a constant cement content, it is evident that as the gangue content increases, the compressive strengths of the backfill specimens under all three crushing methods at 7, 14, and 28 days exhibit a positive correlation trend. Specifically, for the backfill made of coal gangue crushed in two stages with particle sizes larger than 80mm, the 7-day strength values at concentrations of 72% and 76% are 1.263 MPa and 1.807 MPa, respectively, indicating a 43% strength increase with higher gangue content. The 7-day strength of the backfill made from full-size range coal gangue after single-stage crushing increases by 57%, while that after double-stage crushing doubles. The later strength of the coal gangue backfill is more responsive to changes in mass concentration compared to the early stage. At 28 days, the strengths of all three groups of backfills with different crushing methods increase by approximately 50%. Therefore, it can be deduced that appropriately elevating the coal gangue content during cement hydration can bolster the mechanical properties of the backfill, achieving higher overall strength.

3.3. Water secretion rate

Water bleeding rate is a key indicator used to assess the water retention performance of filling slurries. It refers to the percentage of water that is separated from the top layer of the slurry over a specified period, relative to the total mass of the slurry. A high water bleeding rate indicates poor water retention, meaning that water is easily expelled to the surface, which can negatively impact the workability of the slurry [16]. The water bleeding rate of slurries can be calculated using the following formula [17]:

$$\eta = \frac{V}{V_0} \times 100\% \tag{1}$$

In the formula, η represents the water bleeding rate (%) ; V denotes the volume of water separated from the slurry (ml), and V_0 refers to the original volume of the slurry (ml).

This experiment examined the water bleeding performance of gangue filling slurries produced through three different crushing methods. As shown in Tables 10 to 12, the results indicate that double-stage crushing of coal gangue with particle sizes larger than 80mm significantly affects the slurry's water bleeding, with a water bleeding rate reaching 1.71%. A positive correlation can be observed between the particle size of the crushed coal gangue and the water bleeding rate of the slurry. However, since the fine particle fraction makes up a larger proportion after double-stage crushing of full-size range coal gangue, the water bleeding rate is relatively low. Under varying concentrations and gangue contents, the water bleeding rate decreases as concentration increases and gangue content decreases.

Table 10. The water bleeding rate of the backfill slurry made from coal gangue after double-stage crushing with particle sizes above 80mm

Number	Concentration (%)	Coal gangue mixing (%)	water bleeding rate (%)
1	72	51	1.71
2	74	53	1.21
3	76	55	0.67

Table 11. The water bleeding rate of the backfill slurry made from coal gangue that has undergone double-stage crushing using full-size range coal gangue

Number	Concentration (%)	Coal gangue mixing (%)	water bleeding rate (%)
1	72	51	1.38
2	74	53	0.86
3	76	55	0.49

Table 12. The water bleeding rate of the backfill slurry made from coal gangue that has undergone single-stage crushing using full-size range coal gangue.

Number	Concentration (%)	Coal gangue mixing (%)	water bleeding rate (%)
1	72	51	1.52
2	74	53	0.81
3	76	55	0.54

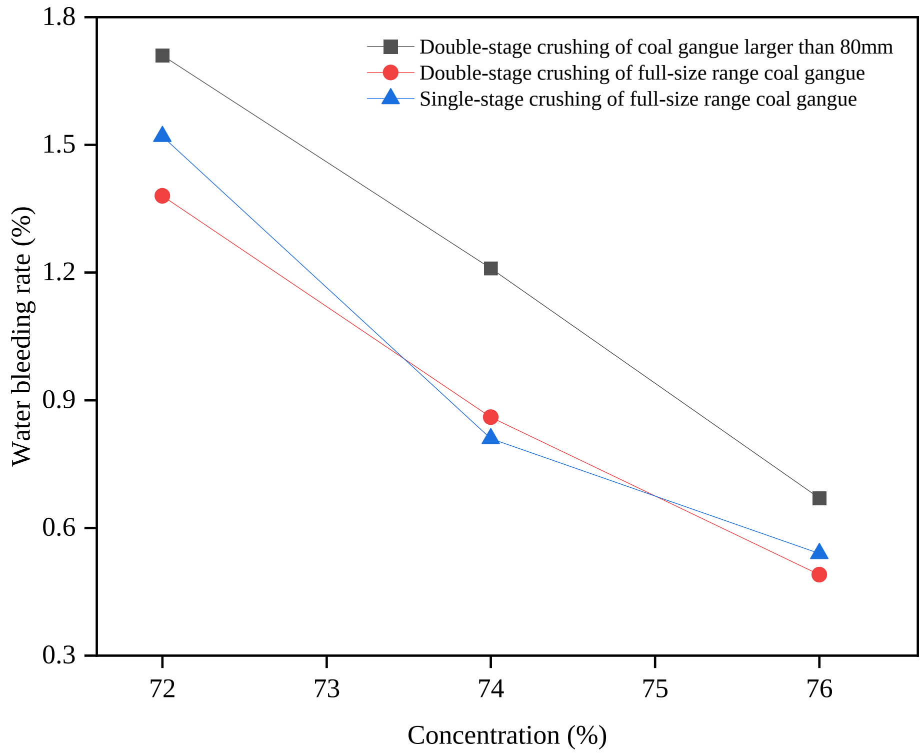

Figure 9. Water bleeding rate curves of filling slurries under different crushing methods

As depicted in Figures 7 to 9, the incorporation of coarse-grained coal gangue significantly improves the water bleeding properties of the backfill slurry. As the concentration of coal gangue increases, the water bleeding rate gradually decreases. The porous nature of coal gangue aids in water absorption. When the content of fine-grained coal gangue is lower, its ability to inhibit water bleeding in the slurry diminishes, resulting in higher pore water content and a decrease in free water during slurry preparation. This phenomenon weakens the rheological properties and cohesion of the backfill slurry, ultimately causing slurry segregation and increased water bleeding.

In terms of crushing methods, the water bleeding rates of both single-stage and double-stage crushing of full-size range coal gangue are comparable. However, after double-stage crushing, the proportion of fine-grained coal gangue increases. These finer particles contribute to the development of pores within the gangue, compacting its internal structure and enhancing its water adsorption capacity. Consequently, with a stronger water-fixing ability, a substantial amount of water is absorbed during the reaction process, leading to a lower water bleeding rate compared to single-stage crushing.

The concentration of the slurry also plays a crucial role in influencing the water bleeding rate. As the concentration of the backfill slurry increases, the water bleeding rate notably decreases. For the slurry produced from coal gangue with particles larger than 80mm after double-stage crushing, the water bleeding rates at concentrations of 72% and 76% are 1.71% and 0.67%, respectively, representing a 1.5-fold decrease. Similarly, for both single-stage and double-stage crushing of full-size range coal gangue, the reduction in water bleeding rates is comparable, with a decrease factor of 1.8 times.

An increased proportion of coal gangue in the mixture leads to a reduction in the pores and overall porosity of the backfill material, thereby enhancing its water retention capacity. Additionally, a higher slurry concentration reduces the proportion of mixing water, decreasing the amount of free water within the slurry. Consequently, the proportion of bound and adsorbed water within the mixture's structure increases, improving the slurry's resistance to segregation and leading to a relative decrease in the water bleeding rate.

4. Comprehensive Evaluation

Based on tests of uniaxial compressive strength and bleeding rate for coal gangue fillings, Table 13 summarizes the advantages and disadvantages of three different crushing methods for coal gangue. The particle size distribution of raw coal gangue is relatively dispersed and not screened, with fine-grained particles being unsuitable as coarse aggregates for fillings. After double-stage crushing of full-size coal gangue, the particle size becomes finer, and the specific surface area increases, requiring more cement paste for coating. This additional paste hinders the dehydration of the filling, thereby reducing its strength. Furthermore, double-stage crushing consumes more energy.While single-stage crushing of full-size coal gangue consumes less energy, the crushing effect is less efficient, resulting in coarser particles that hinder strength development. However, by screening the coal gangue and applying double-stage crushing to particles larger than 80mm, a more uniform particle size distribution can be achieved. This method results in well-graded sand particles, with larger and smaller particles filling each other's gaps. As a result, internal voids are reduced, leading to a denser structure within the coal gangue filling. This dense structure not only enhances the compressive strength of the coal gangue filling but may also improve its flexural and tensile properties.

Table 13. Advantages and Disadvantages of Different Coal Gangue Crushing Methods**.**

Crushing method	Grain size	Uniaxial compressive strength	Water bleeding rate
Double-stage crushing with particle sizes above 80mm	Moderate modulus of fineness	Better	Larger
Double-stage crushing using full-size range coal gangue	Modulus of fineness too small	Rather poor	Smaller
Single-stage crushing using full-size range coal gangue.	Excessive fineness modulus	Average	Smaller

Considering the performance of coal gangue fillings under various crushing methods, double-stage crushing of coal gangue particles larger than 80mm proves to be more effective in enhancing the quality of the fillings. To optimize the utilization rate of coal gangue, the process flow shown in *Figure 10* can be considered: After screening the raw coal gangue, particles larger than 80mm undergo double-stage crushing and are subsequently used for mine filling. Since the application of coal gangue in other industries (such as the building materials, chemical, and agricultural sectors) often requires smaller particle sizes to meet specific production needs, using screened coal gangue can reduce the overall processing steps. This, in turn, promotes higher utilization rates of coal gangue and lowers associated costs.

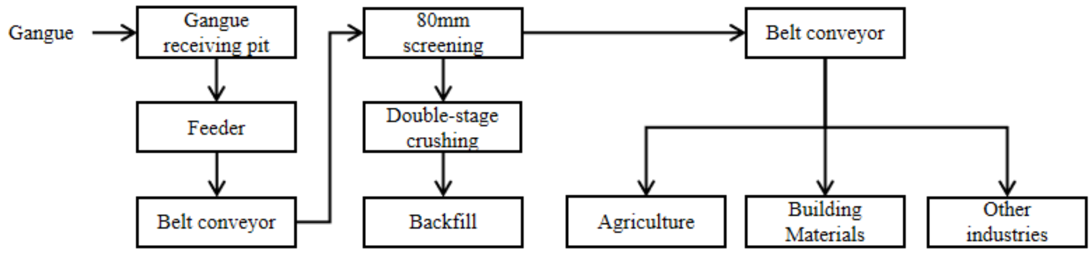

Figure 10. Process flow for utilization of coal gangue**.**

5. Conclusions

This study analyzed the effects of three crushing methods: crushing coal gangue particles larger than 80mm, single-stage crushing of full-size range coal gangue, and double-stage crushing of full-size range coal gangue. It examined the physical and mechanical properties of cemented filling materials made from coal gangue with different particle size combinations and drew several conclusions, summarized as follows:

(1) Among the various factors influencing coal gangue crushing, particle grading and fineness modulus play crucial roles. The experiment revealed that coal gangue particles after single-stage crushing were relatively coarse. Compared to both single-stage and double-stage crushing of full-size range gangue, crushing particles larger than 80mm yielded better results, with good grading that imparted excellent workability to the filling slurry and promoted the development of uniaxial compressive strength in the cemented filling material. The fineness moduli of the slurries produced by single-stage crushing of full-size range gangue and by crushing particles larger than 80mm were relatively large, which led to issues such as water bleeding and segregation in the slurry.

(2) As the concentration of the slurry increases, incorporating more gangue enhances the strength of the filling body. With a constant cement content, experiments showed that the compressive strength of the filling specimens, under different particle sizes and crushing levels, increased as the gangue content rose. In all three experimental groups, a positive correlation was observed between the compressive strengths at 7, 14, and 28 days. Furthermore, medium- to coarse-sized gangue particles improved the mechanical properties of the cemented filling body during cement hydration, resulting in higher compressive strength.

(3) The particle size and content of gangue affect the water bleeding rate of the filling material. Coarse-grained coal gangue improved the water bleeding property of the filling slurry. The water bleeding rate was the lowest after double-stage crushing of full-size range gangue, as the proportion of fine-grained gangue increased, leading to better water-fixing ability. As the slurry concentration increased, the water bleeding rate decreased. An increase

in gangue content reduced the pore structure and porosity of the filling body, and the reduction in mixing water exacerbated slurry segregation.

In summary, the analysis of particle grading, filling body strength, and water bleeding rate after applying three different crushing methods to coal gangue shows that the crushing effect significantly impacts cemented filling materials. Variations in outlet grading have different degrees of influence on the performance of the filling body. Overall, the gangue filling effect based on crushing is substantial, effectively addressing the issue of coal gangue solid waste storage and offering significant potential for the construction of green mines and waste-free disposal. Besides the factors considered in this experiment, the performance of cemented filling materials is also influenced by slurry fluidity, slump, and bulk density. Future research should explore these additional performance indicators. Moreover, the long-term durability of coal gangue materials with different gradations could also be an area for further investigation.

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