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Article

Research on the Gangue Paste Backfill Process System Using Coal Gangue at Bulianta Coal Mine

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Abstract: To promote the proper disposal of local coal mine solid waste, such as coal gangue, improve the resource recovery rate of the mine, and ensure the safe use of surface buildings, Bulianta Coal Mine aims to utilize coal gangue and fly ash for cemented paste backfill. The goal is to establish a backfilling technology suited to the geological and mining conditions of the continuous mining and backfilling areas, specifically for roadway strip filling. This study analyzes the physical properties of the backfill slurry, determines the process parameters, and calculates the required backfill volume through laboratory tests on properties such as fluidity and bleeding rate. Based on these findings, the study outlines the aggregate processing process, which includes full-size double-stage crushing, and the pumping process with continuous mixing preparation. The proposed paste backfill system is reliable, with no leakage of coal gangue paste or pipeline blockages during transportation. This system enables the safe and efficient mining of overburden coal resources, promotes the recycling of solid waste, and contributes to the development of green mining practices.

Keywords: coal gangue, cemented paste backfill, double-stage crushing

1. Introduction

The sustained and large-scale extraction of coal resources has driven rapid economic growth in China, but it has also resulted in a range of environmental issues, such as the massive accumulation of coal gangue waste, surface subsidence, and ecological degradation

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[1-4]. Additionally, fly ash, a byproduct of coal combustion, has become the largest source of industrial solid waste emissions in China. Containing harmful heavy metals and radioactive substances, fly ash contributes significantly to air, water, and soil pollution [5-8]. To address these environmental challenges and promote sustainable development, backfill mining has emerged as an ideal solution [9]. This method involves injecting backfill materials composed of solid waste (such as coal gangue, fly ash, and slag) and water into the gob areas left after coal extraction. It not only supports the overlying strata and effectively controls surface subsidence, but also enables the comprehensive utilization of coal solid waste, making it a key technology for environmentally friendly coal mining [10].

The quality and cost of backfill are critical factors influencing the widespread adoption of backfill mining methods [11]. Therefore, implementing a backfill process with low investment, simple technology, and reduced filling costs can facilitate safe, efficient, and sustainable mining operations [12]. For example, Zhang Hua et al. optimized the tailings backfill ratio and used energy-efficient equipment to mitigate geological hazards such as surface collapse and slope instability in a copper mine undergoing deep mining. This work provides valuable insights for addressing gob areas in aging mines and preventing geological disasters [13].

To promote the construction of green mines while ensuring the safe use of surface structures, a roadway-strip backfill system has been established in the continuous mining and backfill areas of the central and eastern regions. Based on this system, the present study determines the process parameters for preparing coal gangue paste backfill slurry through experiments on fluidity, bleeding rate, and strength. Additionally, the paper outlines the process flow and filling capacity of the backfill system, taking into account the mine's production situation. This approach not only addresses the challenges of coal gangue paste backfill and transportation, but also integrates the resource utilization of solid waste with the mitigation of coal mining subsidence. By reducing the land occupation by coal gangue piles and minimizing environmental pollution, this strategy contributes to the sustainable development of mines.

2. Parameter of coal gangue backfill paste

2.1 Backfill materials

As a backfill aggregate, coal gangue needs to undergo crushing, with the particle size controlled to within 10 mm. The particle size distribution after crushing is shown in Table 1. Coal gangue is primarily composed of minerals such as kaolinite, quartz, albite, mica, chlorite, and microcline. It has a true density of 2.57 t/m^3 and a pH of 7, classifying it as Class I general industrial solid waste.

Table. 1 Test results of particle size distribution for crushed coal gangue.

Particle size (mm)	Volume (%)	Particle size (mm)	Volume (%)
+9.5	0.53	+9.5	0.53

-9.5~+4.75	2.69	+4.75	3.22
-4.75~+2.36	6.59	+2.36	9.81
-2.36~+1.18	7.07	+1.18	16.88
-1.18~+0.6	14.51	+0.6	31.39
-0.6~+0.3	20.24	+0.3	51.63
-0.3~+0.15	19.63	+0.15	71.26
-0.15	28.74	-0.15	28.74

Fly ash produced by a power plant near the coal mine has been selected to partially replace cement in the backfill. Figure 1 shows the particle size distribution of the fly ash. It consists of 91.64% of particles smaller than 74 μm (finer than 200 mesh) and 70.16% smaller than 38 μm (finer than 400 mesh). The residue retained on a 0.045 mm square-hole sieve is 23.87%, classifying it as Grade II fly ash. The main minerals present include quartz, calcite, and albite, with a pH value of approximately 12 and a true density of 1.91 t/m³.

Ordinary Portland Cement (OPC, P.O. 42.5, Nanfang Cement Co., Ltd, China) was used for the backfill, with a density of 3.000 g/cm³. The water used for backfilling is domestic water from the mine, which is slightly alkaline.

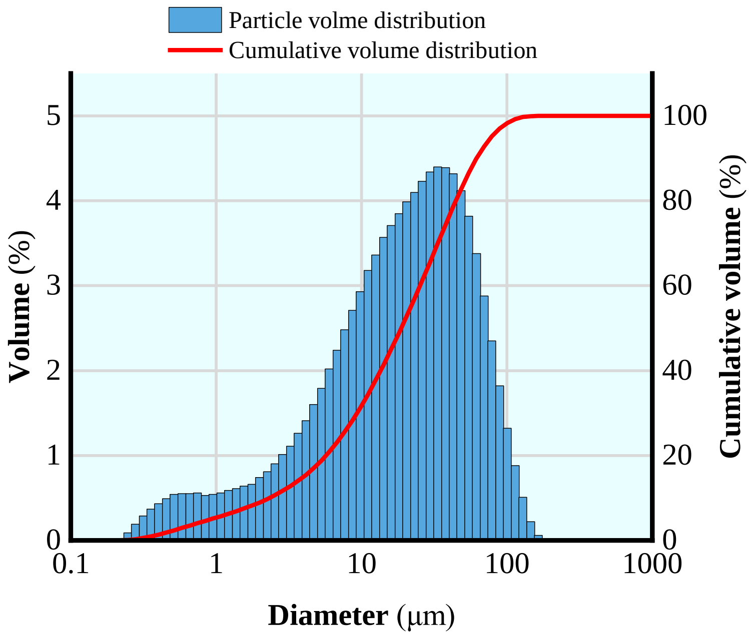

Figure 1. Distribution of fly ash particle size.

2.2 Backfill process parameters

This paper presents research on low-compression gangue paste backfill materials and high-contact-with-roof backfill techniques. The determination of backfill process parameters is based on various indicators and criteria, including the flow characteristics of the paste backfill slurry, slurry stability, pumpability, early-stage strength, and later-stage strength [14].

2.3 Requirements for coal gangue paste backfill indicators

(1) The backfill should be performed via pumping, with the slump of the freshly mixed paste backfill slurry not less than 240 mm, ideally controlled within the range of 260 ± 20 mm.

(2) The pumpable duration of the slurry should be no less than 2 to 4 hours, meaning that after mixing with water and allowing it to stand for 2 to 4 hours, the slurry should still be pumpable. The paste slurry should exhibit no significant stratification, and its slump should remain within the range of 180-200 mm.

(3) The bleeding rate of the paste slurry should be no more than 3%, and the degree of stratification should be less than 2 cm.

(4) Under laboratory conditions, the uniaxial compressive strength of the slurry should be no less than 0.1 MPa after 8 to 10 hours, and no less than 5.0 MPa after 28 days.

(5) During paste backfill mining, the contact rate of the backfill material with the roof should be no less than 95%.

2.4 Parameters for backfill process

Based on the recommended mixing ratio parameters—coal gangue to cement ratio ranging from 12:1 to 4:1, fly ash content between 20% and 60%, and a filling paste mass concentration of 70–80%—experiments were conducted in the laboratory using coal gangue, fly ash, and other materials. The bleeding rate, slump, density, rheological parameters, setting time, and strength at various ages of the materials were measured. The process and some of the results are presented in Figure 2 and Table 2.

Based on the recommended mixing ratio parameters: coal gangue to cement ratio ranging from 12:1 to 4:1, with fly ash content between 20% and 60%, and a mass concentration of the filling paste at 70~80%. Experiments on the mixing ratio were conducted in the laboratory using coal gangue, fly ash, and other materials. The bleeding rate, slump, density, rheological parameters, setting time, and strength at various ages of the materials were measured. The process and some of the results are shown in Figure 2 and Table 2.

Figure 2. Experimental procedure**.**

Table 2. Experimental data from phased testing of filling paste**.**

Number	Bleeding rate	Density / t/m³	Slump /mm	Rheological parameters /pa·s	Yield stress /pa	Strength /MPa		
						7d	14d	28d
Ratio 1	2%	1.752	265	5.15	399.882	3.29	6.27	7.3
Ratio 2	2%	1.711	268	4.841	424.524	2.03	4.54	5.38
Ratio 3	2%	1.899	263	5.775	648.853	1.49	3.87	4.63
Ratio 4	2%	1.851	261	5.517	379.915	1.53	2.76	2.36
Ratio 5	2%	1.865	260	3.826	139.55	0.69	2.39	1.96

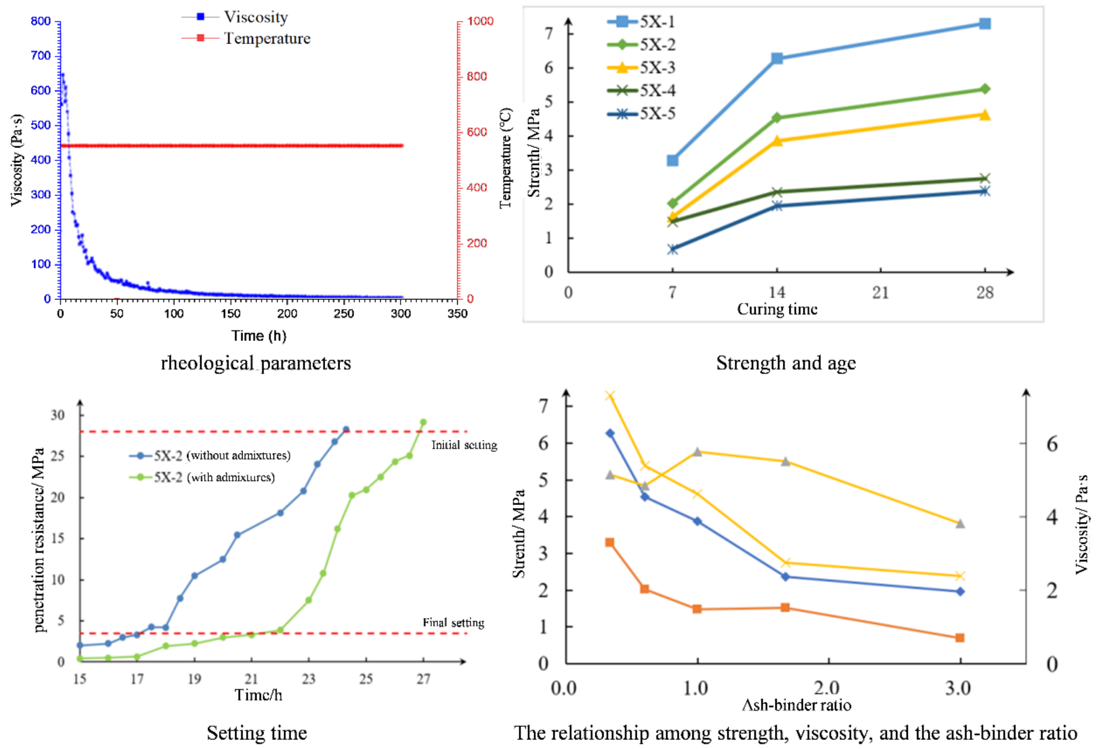

Figure 3. Graph depicting partial results of paste performance parameter curves.

Phased experiments have shown that the developed mixing ratios generally meet the requirements for the fluidity and strength of the backfill materials. Considering the experimental results for the paste backfill material ratios as a whole, the selected range for the filling material ratio is as follows: a coal gangue to cement ratio of 8:1 to 4:1, fly ash content of 20% to 50%, and a mass concentration of the backfill paste between 74% and 76%.

2.5 Applicable conditions for coal gangue backfill paste

This study can be selected and adapted based on different conditions and geological environments. Underground backfilling is suitable for mines with unstable roofs, as it effectively reduces the risk of roof collapse and surface subsidence. However, the main challenges of this technology are underground transportation and the risk of secondary pollution. In contrast, surface backfill technology is better suited for mines with stable roofs and significant surface subsidence. It helps control surface subsidence while promoting land reclamation, but it also presents challenges related to land use and increased transportation costs due to subsidence. The combined up-hole and down-hole backfill method integrates the advantages of both approaches and has high technical maturity. It can comprehensively address issues of roof collapse and surface subsidence, aiding land reclamation. However, it also faces the dual challenges of transportation and additional processing costs.

3. Backfill system process and backfill effect

3.1 Ground backfill process

The ground backfill process of the paste backfill system at this coal mine consists of two main parts: the aggregate processing process and the mixing, proportioning, and pumping process. The backfill technology used in this study involves crushing coal gangue in two stages. In the primary crushing stage, gangue (500 mm to 0 mm) is reduced to -150 mm, and in the secondary stage, it is further crushed to -10 mm. The crushed gangue is then mixed with cement, fly ash, water, and other materials to produce the qualified paste backfill.

3.1.1 Aggregate processing flow for paste backfill

The particle size requirements for gangue used in the paste backfill are as follows: the maximum particle size should be ≤10 mm, with 90% of the particles ≤5 mm. Specifically, 50% of the particles should fall within the range of 0.5 to 0.075 mm, 25% within 0.6 to 2 mm, and 15% within 2 to 5 mm. In addition to meeting the maximum particle size requirement for gangue, the gangue crusher plays a crucial role in ensuring the proper particle size distribution necessary for producing high-quality paste. Experimental comparisons have shown that the particle sizes of crushed coal gangue are relatively consistent. Therefore, a two-stage crushing process is employed for the coal mine gangue, with coarse crushing in the first stage and fine crushing in the second. The high-fine crusher serves as the core equipment. Under normal filling conditions, the gangue preparation capacity is calculated at 300 t/h. To allow for a safety margin, the capacity for gangue conveying, crushing, screening, and feeding should reach 400 t/h.

The detailed aggregate processing flow is illustrated in Figure 4 below and is described as follows: Raw gangue is transported to the storage yard by truck and fed into the belt conveyor by a belt feeder located under the receiving pit. It is then transferred to the coarse crushing and screening workshop for the first stage of crushing. Gangue ≤500 mm is crushed to -150 mm by a jaw crusher and transported to the fine crushing workshop for the second stage, where it is further reduced to -10 mm by a high-fine crusher. The crushed gangue is then transported back to the coarse crushing and screening workshop, where it is screened and classified by a cylindrical screen (φ10 mm). The oversize material (+10 mm) is sent back to the fine crushing workshop for further processing, while the undersize material (10~0 mm), which is the qualified aggregate, is transferred to the finished gangue storage yard for storage. From there, it is fed by a belt feeder located under the receiving pit into another belt conveyor and transported to the filling workshop for paste preparation.

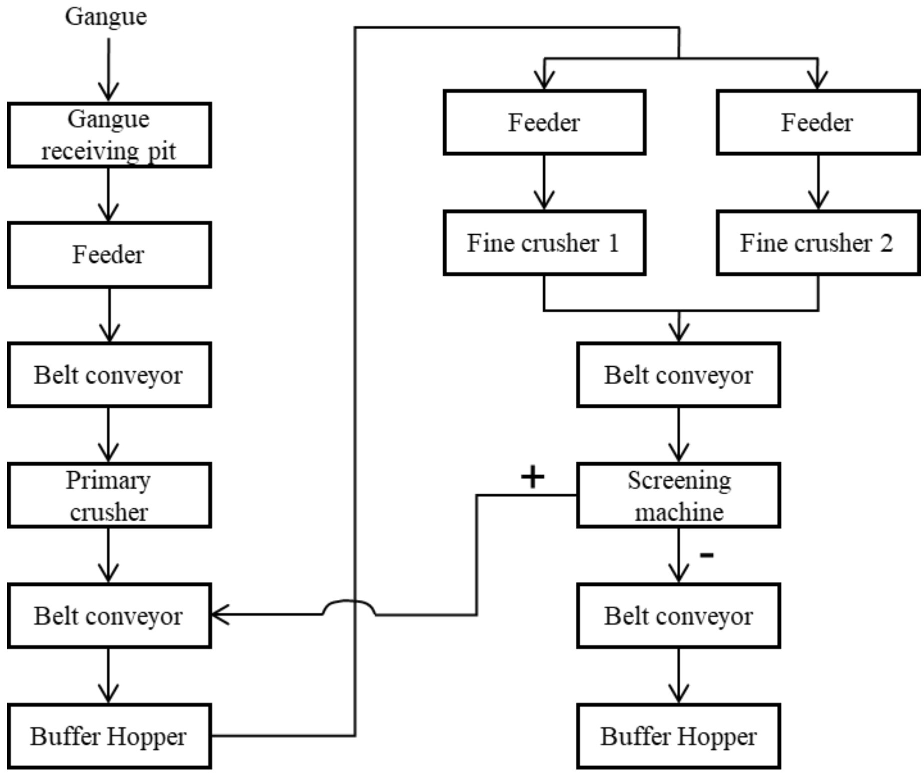

Figure 4. Coal gangue processing flow.

3.1.2 Mixing, proportioning, and pumping process flow

(1) Aggregate Proportioning

The gangue is fed into the weighing hopper below by a belt feeder located under the raw gangue storage yard, in accordance with the material requirements. After weighing, the aggregate is transferred to the aggregate weighing hopper in the filling workshop to complete the proportioning process. Once proportioning is finished, the aggregate is sent to the mixer, and the cycle repeats for continuous aggregate proportioning.

(2) Powder Material Proportioning

The powder materials used for filling primarily consist of fly ash and cement, both stored in cylindrical steel silos to meet environmental requirements. A screw feeder is installed at the bottom of each silo to transfer the powder material into the weighing hopper in a closed manner, enabling continuous proportioning. After proportioning, the powder material is added to the mixer.

For liquid proportioning, the filling liquid is mainly water, sourced from a production water tank. A water pump is installed in the tank to transfer the water to the water weighing hopper in the filling workshop. The water is then pressurized by a pipeline pump and fed into the mixer.

Two double-horizontal shaft high-strength mixers are selected, with a rated batch paste volume of 3.5 m^3, a dry material capacity of 5.25 m^3, and a production capacity of (3600/90) × 3.5 × 2 = 280 m^3/h, which exceeds the required working capacity of 250 m^3/h for the mixing and proportioning system.

(3) Liquid Proportioning

The filling liquid primarily consists of water sourced from a production water tank, which is pumped into the water weighing hopper in the filling workshop. The water is then pressurized and fed into the mixer.

(4) Pumping and Filling

After the paste filling material is uniformly mixed in the mixer, it is transferred to a high-flow filling pump through a buffer hopper. The filling paste is then continuously pumped through pipelines to the mining and filling workface. A flow diagram of the filling process is shown in Figure 5.

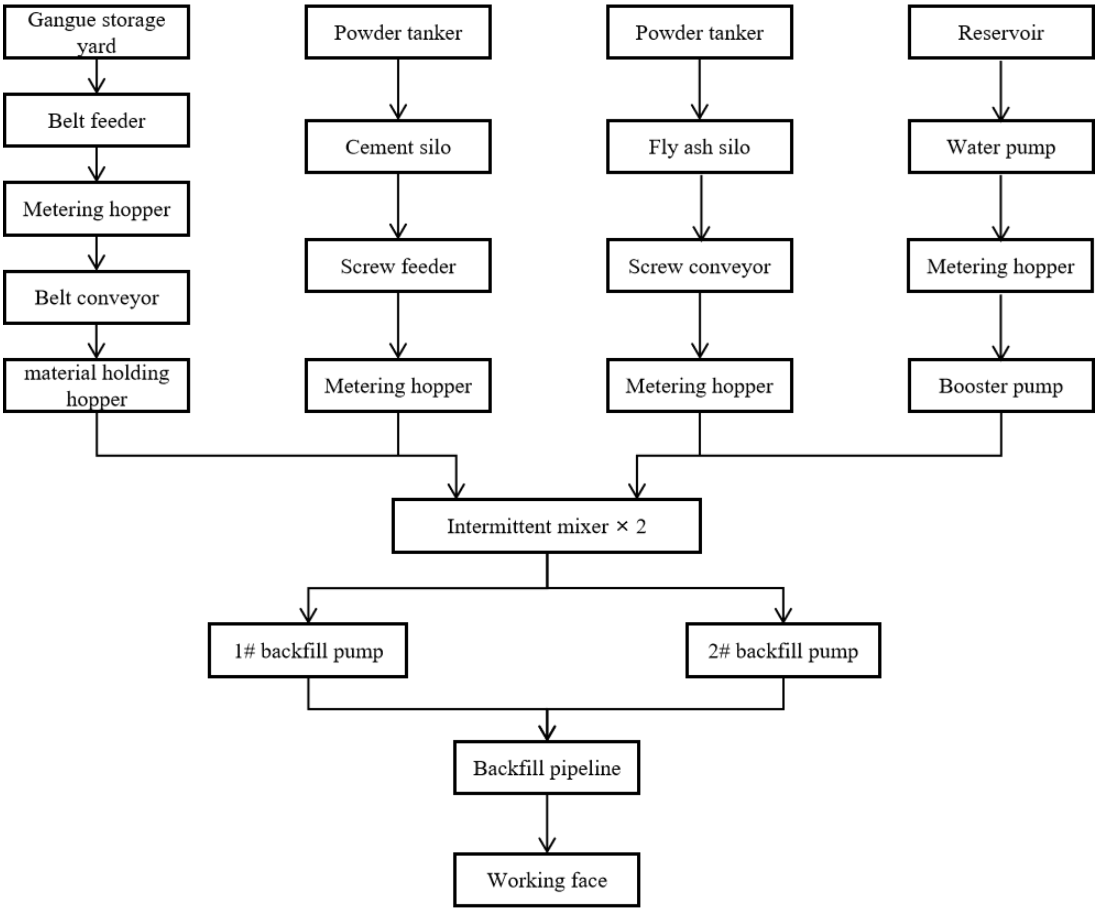

Figure 5. Pumping and backfill process

3.2 Backfill evaluation

Through the precisely determined filling process parameters and optimized process flow in this study, the stability of the filling operation is ensured, while achieving safe and reliable transportation of the filling slurry. This technology has developed into a technical system for roadway strip filling operations that is well-suited to the geological conditions of continuous mining and filling areas. With the assistance of the ground filling station, the technology ensures that the gangue paste does not leak during transportation and that the pipelines remain unobstructed, thereby achieving high recovery rates and safely and efficiently extracting overlying coal resources. Additionally, it enables the full utilization of solid waste generated by local coal mines while ensuring the safe use of surface buildings and structures.

Compared with various parameters of backfill technologies, such as backfill mechanical properties, solid-liquid two-phase flow transportation, backfill body behavior mechanisms, and slurry preparation, the coal gangue paste filling process system offers five key advantages:

1. The backfill working face requires no additional equipment other than the backfill pipeline.
2. The backfill material's strength can support the roof within 8 hours and control roof subsidence.
3. The backfill effect is significant, reducing the depth of damage to the base plate caused by mining pressure, which helps prevent water ingress under pressure.
4. It enables coal pillar-free mining, and tunneling along the goaf reduces the excavation rate of the mining tunnel by 10,000 tons.
5. There is an ample supply of filling materials, with gangue and fly ash locally sourced, which helps minimize transportation costs.

However, there are two potential disadvantages:

1. The initial investment required for constructing the ground station is high.
2. The lack of external transportation power means the system relies on potential energy self-flow, which poses a risk of pipeline blockages. Its effectiveness is completely dependent on the material ratio.

The gangue backfill process not only increases coal production, improves safety, and reduces the costs associated with village relocation and land damage compensation, but it also mitigates the environmental impact of coal mining on local land and groundwater resources. Moreover, it helps recycle solid waste, turning it into valuable resources. This new technology offers significant economic and social benefits, making it a highly advantageous solution.

4 Economic cost evaluation and environmental impact assessment

4.1 Economic cost analysis

The financial evaluation indicators are presented in Table 3. Based on the data, the after-tax internal rate of return (IRR) for the project investment is 15.6%, which exceeds the industry’s benchmark rate of return of 10%. Additionally, the after-tax net present value (NPV) is positive. These profitability indicators suggest that the project is financially viable and demonstrates strong profitability.

Table 3. Table of main financial evaluation indicators**.**

No.	Name	Index	Unit
1	Financial internal rate of return of project investment (%) (after income tax)	15.60	%
2	Financial internal rate of return of project investment (%) (before income tax)	19.61	%
3	Financial internal rate of return of project capital (%)	15.60	%

4	Project investment payback period (years) (after income tax)	6.88	Years
5	Project investment payback period (years) (before income tax)	5.77	Years
6	Project investment financial net present value (after income tax)	10083.54	Ten thousand yuan
7	Project investment financial net present value (before income tax)	11183.24	Ten thousand yuan
8	Financial net present value of project capital (after income tax)	4845.16	Ten thousand yuan
9	Total investment return rate (%)	15.75	%
10	Investment profit rate	15.75	%
11	Investment profit and tax rate	29.8	%
12	Project capital net profit margin	17.49	%
13	Break-even point (proportion of output)	89.21	%

The estimated composition of this process system is shown in Table 4. According to the calculations, the investment in the backfill station is distributed as follows: infrastructure projects account for 31.37%, equipment purchase for 24.37%, installation for 29.97%, other costs for 10.44%, and project reserves for 3.85%. Based on these figures, the investment in equipment and installation constitutes a significant proportion. Since the continuous mining and backfilling project is a research initiative involving a highly advanced system, the overall feasibility of the coal gangue paste backfill system is considered to be relatively high.

Table 4. Summary table of estimated budget for ground filling stations**.**

No.	**Production components**	**Estimated value (10 thousand Yuan)**					**TOCI (yuan/ton)**	**IP (%)**
		Inf	**Equ**	**Ins**	**Others**	**Total**		
1	Raw material dump	343.97	284.86	59.94		688.76	6.89	6.89
2	Rough crushing workshop	169.62	206.10	50.78		426.50	4.26	4.27
3	Fine crushing workshop	194.77	57.05	35.74		287.56	2.88	2.88
4	Waste rock dump	277.48	139.61	27.90		444.99	4.45	4.45
5	Backfill system	240.27	791.71	928.22		1960.19	19.60	19.61
6	Conveyor & Transfer station	911.04	397.70	83.61		1392.35	13.92	13.93
7	Weighbridge Room	24.19	22.0	13.50		59.69	0.60	0.60
8	Communication & Fire protection system		33.68	17.70		51.38	0.51	0.51
9	Electric supply system	124.71	320.07	478.35		923.13	9.23	9.23
10	Water supply & Drainage	317.65	99.21	94.72		511.58	5.12	5.12
11	HVAC	71.20	84.76	670.73		826.69	8.27	8.27

12	Security Room	8.83				8.83	0.09	0.09
13	Site facilities	452.21				452.21	4.52	4.52
14	Scientific research procurement			534.92		534.92	5.35	5.35
15	Other construction costs				1043.61	1043.61	10.44	10.44
16	Project reserve (4%)				384.50	384.50	3.85	3.85
Total static investment		3135.94	2436.73	2996.11	1428.11	9996.89	99.98	100.0
Ton of coal investment (yuan/ton)		31.36	24.37	29.96	14.28	99.98		
Investment Proportion (%)		31.37	24.37	29.97	14.29	100.00		

Re：Inf——Infrastructure ; Equ——Equipment ; Ins——Installation;

TOCI——Ton of coal investment (yuan/ton) ; IP——Investment Proportion (%).

4.2 Environmental Impact Assessment

The coal gangue paste backfill system complies with relevant Chinese national regulations and environmental protection policies, which aim to scientifically and objectively assess the direct impacts and potential risks of the system's construction on the surrounding natural environment, ecosystem, social economy, and human health.

4.2.1 Followed environmental protection standards

Air: "Ambient Air Quality Standard" (GB 3095-2012)

Surface Water: "Surface Water Environmental Quality Standard" (GB 3838-2002)

Groundwater: "Groundwater Environmental Quality Standard" (GB/T 14848-2017)

Acoustic Environment: "Acoustic Environment Quality Standard" (GB 3096-2008)

Domestic Waste Disposal: "Domestic Waste Landfill Pollution Control Standard" (GB16889-2008)

Noise: "Industrial Enterprise Factory Boundary Environmental Noise Emission Standard" (GB12348-2008), "Construction Site Boundary Environmental Noise Emission Standard" (GB12523-2011)

4.2.2 Analysis of the production of major pollutants

The main pollutants generated during the construction of the entire system, as listed in Table 5, include dust, wastewater, solid waste (domestic waste), and noise. These pollutants originated from the production system at the backfill station, production wastewater, domestic waste, and the operation of machinery and equipment. According to Table 5, the emissions of various pollutants complied with the relevant emission standards. The total emissions of all pollutants were within the prescribed control limits. The system met the environmental protection requirements set by the local government. However, to further minimize the impact on the environment and human health, effective control measures should be implemented. These include installing dust removal equipment, constructing wastewater treatment facilities, setting up a waste classification and recycling system, and installing noise insulation equipment.

Table 5. Major pollutant generation table**.**

No.	Classification	Name	Production	Pollutant production
1	Dust	Backfill system	6720.00t/a	4000.00mg/Nm³
2	Sewage	Sewage production	37.80m³/d	SS=600～3000mg/L Oil= 1.0～15mg/L CODCr= 100～300mg/L
3	Solid waste	Household waste	5.84t/a	1.0kg/person ·d
4		workshop	Screen, Crusher	98dB(A)
5	Noise	Conveyor equipment	Conveyor belt	90dB(A)
6		Pump	Water Pump	75dB(A)

5. Conclusion and Discussion

Based on the specific production, technical, and economic conditions of a certain coal mine, experiments on coal gangue-gypsum paste backfill materials and research on backfill technology were conducted. The following conclusions were primarily drawn from this study:

(1) A backfill system with a capacity of 250m³/h is sufficient to meet the mine's backfill requirements. The designed service life of this system is 12.5 years. The selected backfill materials include coal gangue, fly ash, cement, and water, with a comprehensive ratio range of coal gangue to cement being 8:1 to 4:1. The fly ash content ranges from 20% to 50%, and the paste backfill material has a mass concentration of 74% to 76%.

(2) The technological process suitable for roadway strip backfill under the geological mining conditions of continuous mining and backfill areas involves high-concentration pump transportation of paste backfill slurry, dual-stage crushing of full-size coal gangue with a high-fine crusher, and continuous mixing preparation using a double horizontal-axis mixer. This backfill system is reliable, capable of achieving leak-proof gangue-gypsum paste, unclogged pipeline transportation, and high-quality backfill.

(3) During the plan implementation, potential problems such as imperfect raw material supplement, electric supply system and auxiliary production facilities upgrade, and transformation are considered. In the later construction process, the units of the raw materials such as gangue, cement, fly ash, etc. will be determined to ensure the raw material supplement of the backfill system; As for equipment maintenance, the upgrade and transformation plan will be determined as soon as possible. The details are made for equipment evaluation, technology selection, cost-benefit analysis, safety risk assessment, which ensure the economic feasibility, safety and efficiency of the plan.

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