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Research Article

Experimental Study on Lead-Smelting Slag as Paste Filling Cementing Material

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Under the current pressure of mineral product price and market competition, as well as the tightening of ecological and environmental protection policies, energy saving, emission reduction and cost reduction, and efficiency increase have become inevitable trends. Lead-smelting slag of smelter, as an industrial byproduct, is harmful solid waste to be eliminated. In this research, a series of experiments on substitute for cement were done for filling cost reduction under premise of guaranteeing the filling strength, using PC32.5 cement as reference cementing material. Meanwhile, with Portland cement clinker, water quenching slag of BF ironmaking, and lead-smelting slag of smelter in different ratios, four cementing materials were made and named as cementing material I, cementing material II, cementing material III, and cementing material IV. Then, the above five cementing materials including PC32.5 cement were mixed, respectively, with tailing and water to prepare paste backfill slurry with different binder-tailing ratio and concentration. Backfill block was made and cured at 20°C; their uniaxial compressive strengths in different curing ages were measured. The result shows the strength of backfill test block using cementing material I (cement clinker and water quenching slag) without lead-smelting slag is far higher than that of test block using PC32.5 cement as cementing material. The strength of block with 16% lead-smelting slag increased dramatically, which was higher than the strength of block using PC32.5 as cementing material. However, the strength of test block decreased when the content of lead-smelting slag reached 32% and 40%. The more lead-smelting slag was added, the worse influence on strength of backfill would be. Because of large specific gravity of lead-smelting slag and low content of CaO, the hydration activity of lead-smelting slag is far lower than that of water quenching slag. Therefore, using moderate lead-smelting slag as substitute for cement will lead to increase of backfill strength and decrease filling cost.

1. Introduction

In the process of mining and utilization of mineral resources, it has a certain negative impact on the surface environment, and in order to minimize the environmental damage caused by mineral mining, green mining is widely advocated. Optimal use of resources and environmental protection should simultaneously be considered. As the most environmental protection mining method, the backfill method has been attached great importance by mining enterprises and gradually applied in mines. Especially in recent twenty years, different backfill methods with various backfill materials according to conditions of mines have played an important role in safe production in mines [1–4]. Whether the backfill mining could be applied in a mine or not is determined by whether the cost of backfill is acceptable to a mine enterprise. If it costs much and could not lead to good economic effects, even safe mining can be ensured, the backfill mining is still not competitive. The cost of backfill is mainly determined by the cost of cementing material, so the development of cementing material is necessary. Presently, development of cementing material is in great demand, and many researches were done by many institutions and enterprises [5–7]. Because the characteristics of backfill materials and engineering conditions vary in mines, the relevant study is relatively complicated. It is necessary to carry out aggregate optimization or physical and chemical modification according to mine's own backfill material conditions [8, 9] to develop suitable cementing material and provide technical basis to dramatic decrease in backfill cost.

In terms of early backfill technology research, the successful experience of some mines in Canada is worthy of reference. These studies focus on the characteristics and key technical issues of backfill technology. These research results promote the development of backfill technology worldwide [10–12]. For the large-scale filling of goaf, the research and application of filling technology in George Fisher Mine (Mount Isa, Australia) in north central Australia is representative. Based on laboratory tests conducted in collaboration with James Cook University, the geotechnical characteristics of tailings and the rheological properties of CPB were summarized. The results described the flow characteristics of behavior of cemented paste with the addition of two cementing materials of 0-6% and CPB concentration of 72-78%. It provides condition for efficient transportation of filling slurry [13]. In Cannington Mine and some other mines in Australia, paste filling is an effective treatment method for mined-out area. Fine tailing particle and a small amount of cementing material are evenly mixed with water, and the filling slurry is transported to goaf by pipe. The backfill method can greatly improve the local and regional stability of surrounding rock and ore body [14, 15].

In terms of the current application of high-concentration paste filling and related technologies and processes, relevant literature points out the technical characteristics of paste filling and its good performance in engineering application, which can provide reference for similar technical research [16, 17]. In the filling process of cemented tailing paste in hard rock mine in North Queensland, Australia, the researchers comprehensively considered the microstructure and long-term mechanical properties of the filling body, filling body was made by using different fly ash base polymer, fly ash mixed cement (FBC), and general cement (GPC), and the strength of the samples was measured. The conclusions confirm that fly ash can partially replace cement as the binder of paste filling body, thus achieve reasonable economic and environmental benefits [18]. In terms of studying the mechanical behavior of cemented paste with pressure sensors, researchers analyzed the early strength and deformation behavior of the cemented paste under different loading conditions and different curing schemes and grasped that the strength of the cemented paste developed rapidly under the coupling action of consolidation, drainage, and suction. This indicates that applying pressure can cause changes in particle position and interior pores, thus leading to changes in strength. Therefore, curing stress can promote cement hydration, which is conducive to the improvement of filling body's strength [19]. As for the paste filling situation of Brunswick Mine in Canada, a study analyzed the operation in the filling process and discussed the technical problems of the mine [20].

In terms of the development and development of backfill cementing materials, relevant literature introduces several important functions of backfill bodies and analyzes fly ash, slag, and phosphogypsum generated in other industrial production as cementing materials. Finally, some proportion with good strength and flow performance are applied to actual production [21–23]. In order to reduce the harmful element pollution and increase strength of filling body, researchers investigated characteristics of the filling body using the phosphorus gypsum when there is fluoride. By means of SEM and EDS imaging techniques to understand the macro and micro structure of fluorine stability related features, it is concluded that the concentration of acid and alkali is the main factor influencing leaching behavior of fluoride conclusion [24]. For the preliminary studies on the application of blast furnace slag and gas quenching furnace slag in mine filling, some studies have evaluated their application and grasped that the use of blast furnace slag and gas quenching furnace slag as cementing materials can play a good role in mine filling, providing a basis for reducing the filling cost [25]. The binder made by fly ash, lime, and desulfurization gypsum is much better to the traditional cementing materials; its filling body can meet the general requirement of mining production [26–30]. Under the action of a variety of activators, the water-quench secondary nickel slag eventually generates silicate hydrate gel material that plays a major role in the later strength of the filling body [31, 32]. In terms of mechanical properties, researchers mixed tailings with a certain amount of fiber to effectively improve the strength of backfill and obtain the compressive fatigue and damage evolution law of backfill, which can provide important theoretical basis for preventing the blasting impact damage of backfill [33]. The effect of alkali blast furnace slag on curing regularity of tailings and their activation properties of paste filling material was investigated [34]. It provides certain reference for engineering design of the material selection and the calculation of pipeline pressure.

In some studies on the development of cementing materials with lead-smelting slag, it was mentioned that lead-smelting slag was used to make concrete blocks, and the influence of lead-smelting slag on the strength of concrete blocks was obtained. Among them, the size of aggregate particles was relatively large, usually ranging from a few millimeters to ten or even dozens of millimeters [35]. From the perspective of material utilization, this research is applied to building materials, and what we want to get is high strength concrete materials. For governance goaf collapse of geological disasters, which used fine aggregate backfilling, the filling material strength is small, so the scales of the construction of concrete material and the goaf filling material particles vary widely. Due to the smaller particles in backfilling materials, it greatly consumed gelled material hydration cement product; thus, the strength is low. In the development of cementitious materials in different industries, blast furnace steel slag is the most widely used material. Due to its special properties, it can have better hydration performance under the condition of full grinding, so as to produce sufficient hydration products and obtain concrete materials with high strength [36–39]. When lead-smelting slag cementitious material was applied as building materials, the performance of concrete column and beam made by fly ash/lead-smelting slag polymer under concentric and eccentric load was analyzed. The study confirmed that the structure performance of fly ash/glass base polymer concrete is similar to that of ordinary Portland cement (OPC) concrete [40]. As a kind of novel exploratory attempt, relevant staff from industrial battery waste of development used battery-smelting slag of a company from Colombia to provide lead slag as aggregate of asphalt mixture, and they found that the lead quadratic residue could be used in the asphalt mixture [41].

In application of low activity of lead-smelting slag as raw material to develop gelled material, after fine grinding, researchers employed compound excitation agent to stimulate lead-smelting slag which was adopted to replace cement to make block, and the results show that the strength of the block can meet the technical requirements. At the same time, filling cost can be reduced [42]. For tailings from a mine in Yunnan, experiments were carried out using lead-smelting slag as cementing material. The selected activator was reasonable, and the strength of paste filling body formed could meet production requirements [43]. As for the influence of sodium silicate gelling agent on the strength of lead-zinc-smelting slag tailing cemented backfill, researchers prepared lead-zinc-smelting slag and cementing paste samples with different sodium silicate addition levels. Subsequent studies found that sodium silicate significantly promoted the gelling activity of cement. It can accelerate the hydration of binder [44]. In order to properly deal with toxic metals in lead-zinc-smelting slag, relevant studies have optimized the sodium silicate modulus, liquid-solid ratio, and curing temperature that affect the strength development by using alkali-activated cementing materials. The results show that the hardening process is related to the composition of binder, the type of leaching agent, and the property and concentration of heavy metals in the waste [45].

As an important raw material output base of Guangxi China Tin Group Co., Ltd., Tongkeng tin mine has a comprehensive grade of more than 20%, and the ore is of high value due to its good beneficial ability of useful elements. With the continuous development of mining, the enterprise has been committed to exploring the path of sustainable development in recent years, actively studying the green mining mode of mineral resources, and has made some achievements in filling system transformation and tailing resource utilization [46, 47]. Because there are smelters around Tongkeng tin mine, water-quenched slag and lead-smelting slag are easy to obtain. Therefore, this paper studied on cement clinker, water-quenched slag, and lead-smelting slag used as filling cementing materials. The ore of the mine contains a variety of useful metals such as tin, lead, zinc, and indium, and the ore value is very high. Improving the recovery rate and reducing the dilution rate are obvious for improving the economic benefit of the enterprise [48, 49]. At present, the production capacity of Tongkeng tin mine is up to 2.2 million t/a. In order to ensure the safe mining of ore body and effectively protect the industrial and civil infrastructure such as surface buildings, it is necessary to carry out research on filling mining technology. For Tongkeng tin mine, high-quality filling body can effectively protect the mining surface and industrial facilities, prevent surface collapse, and improve the recovery rate of high-grade ore resources, creating reliable technical conditions for making full use of limited ore resources. In the filling engineering of mined-out area, the tailings of multimetal ore dressing plant can be utilized, and the goaf area can accommodate tailings, thus greatly prolonging the service life of surface tailings reservoir.

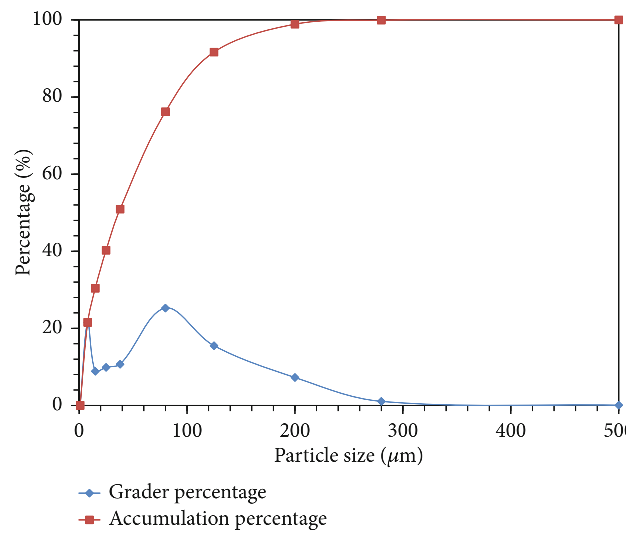

Figure 1: Particle size distribution curve of tailing.

2. Materials

2.1. Tailing. The tailings were from ore-dressing plant of Tongkeng nickel mine. A CILAS1064-laser diffraction particle size analyzer (produced by Cilas, French) was used to determine its grain gradation distribution. The maximum particle size of the device can be tested is 500 μm, and the dry measurement range is 0.1~500 μm, and the wet measurement range is 0.04~500 μm. The particle size distribution curve is shown in Figure 1. The average particle size of tailing is 50.5 μm. Particles of 10%, 50%, 60%, and 90% can, respectively, pass sieve pore's diameter of 2.68 μm, 36.72 μm, 51.50 μm (d_{60}), and 117.84 μm (d_{90}). The concentrator grinds the ore to a finer level to improve the useful metal recovery. According to tabaud theorem, when the uneven coefficient a (= d_{60}/d_{10} = 19.21) is less than 5, it suggests the Tongkeng nickel mine tailing is heterogeneous.

Generally, some chemicals in tailing have effect on the strength of backfill. The effect differs with change of content of chemicals including CaO, MgO, Al_2O_3, SiO_2, S, and Fe. The chemical composition of Tongkeng nickel mine tailing was measured and shown in Figure 2.

The specific gravity of tailing was determined by volumetric flask method, and the loose bulk density was measured by constant volume weighing method. When the loose tailing was in natural packing, natural repose angle, the angle between natural slope and horizontal plane was measured. The parameters of tailing including specific gravity, bulk density, porosity, and slope angle are shown in Table 1.

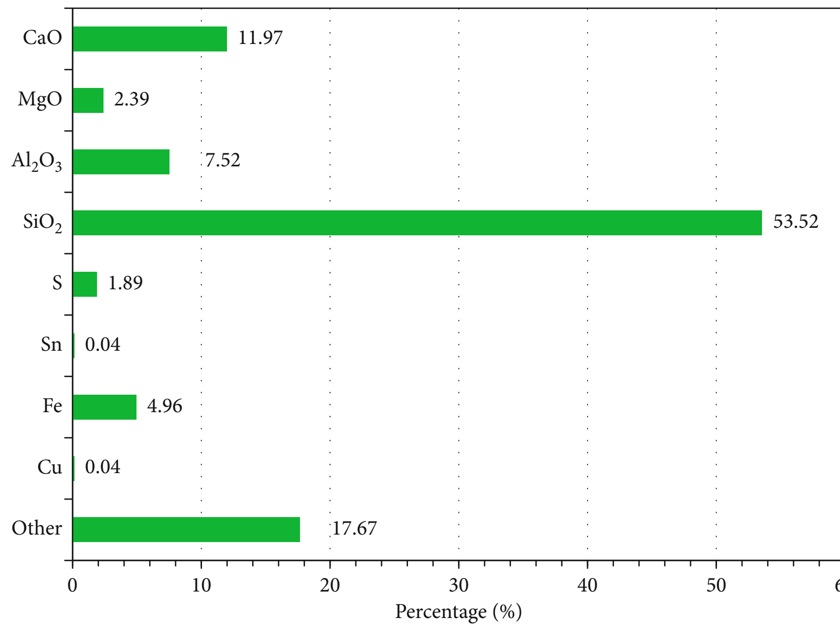

Figure 2: Chemical composition of tailing.

Table 1: Physical properties of the filling material.

Item	Special gravity	Bulk density (t/m^3)	Porosity (%)	Natural repose angle (°)
Tailings	2.997	1.701	43.2	41.0
PC32.5 cement	3.011	1.735	42.3	39.2
Cement clinker	3.312	1.893	42.8	39.0
Water quenching slag	2.693	1.678	37.7	40.8
Lead-smelting slag	2.898	1.786	38.4	38.5

Table 2: Chemical composition of the binder material.

Item	Chemical composition (%) Bulk density (t/m^3) Porosity (%) Natural repose angle (°)						
	CaO	MgO	Al_2O_3	SiO_2	SO_3	FeO	Others
PC32.5 cement	61.55	1.98	6.09	24.65	2.02	2.78	0.93
Cement clinker	63.18	2.79	5.22	21.36	-	6.13	1.32
Water quenching slag	43.15	6.16	14.5	27.77	1.02	3.21	4.19
Lead-smelting slag	18.97	4.79	6.88	26.98	-	30.26	12.12

2.2. Cementitious Materials. Four cementitious materials: PC32.5 cement, cement clinker, water quenching slag of BF ironmaking produced in Liuzhou steel plant, and lead-smelting slag of Huaxi Smelter were used. The PC32.5 cement is reference cementing material to analyze the cementing performance of other cementitious materials.

Water quenching slag and lead-smelting slag were milled to powder. The physical properties of cementitious materials are shown in Table 1. The chemical composition of the binder material is shown in Table 2.

2.3. Water. Water used in experiment is tap water with pH value of 7 in normal temperature environment. And the dosage of water is determined by the concentration of backfill slurry.

3. Experiment

3.1. Slump. Appropriate concentration of backfill slurry not only makes it as good retention and workability but also results in large strength. The gravity transportation concentration is determined by measuring the slump of backfill slurry. As tailing of Tongkeng nickel mine is fine, the fluidity of tailing slurry is similar to that of backfill slurry with addition of cement. Hence, backfill pastes of different concentrations (Table 3) were prepared, and slump values were measured.

The slump–concentration curve is shown in Figure 3. The slump values increase with concentration of slurry. When the concentration of paste was 76% and the slump of backfill paste was 19.5 cm, the gravity transportation of slurry was limited, which was far from requirements of long distance pipeline gravity transportation. When the concentration of paste was 74% and the slump of backfill paste was 24.6 cm, the range of gravity transportation expanded, which still did not satisfy the requirements. When the concentration of paste was 72% and the slump of backfill paste was 26.9 cm, which is in accordance with requirements of long distance pipeline gravity transportation, in addition, water retention and workability were better. When the concentration of paste was 70% and the slump of backfill paste was 28.2 cm, gravity transportation was in a wide range but water retention and workability were worse. Even it was in accordance with requirements of long distance pipeline gravity transportation, a lot of pores are created after the excessive water evaporates, which would have a negative effect on the strength of backfill. Therefore, 72% concentration of slurry in pipeline in the form of whole sliding movement can greatly reduce the wear and tear of pipe and at the same time can realize the gravity of various concentration of slurry, and it has small consolidation speed and shringage. The materials can be used effectively and get better engineering results, and the concentration of 72% is suggested to make sure the strength of backfill meets the requirements of production and better fluidity of slurry.

Table 3: Proportion of tailing slurry.

Series No.	Concentration (%)	Unit mass (kg/m^3)	
		Water (kg)	Tailing (kg)
1	84	363	1908
2	82	397	1808
3	80	428	1713
4	78	458	1624
5	76	486	1540
6	74	513	1460
7	72	538	1384
8	70	562	1312
9	68	585	1243

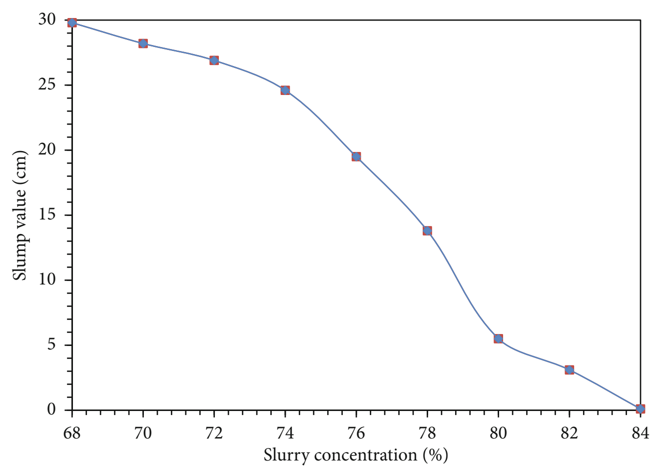

Figure 3: Slump values of tailing slurry.

3.2. Mechanical Test. The backfill materials were, respectively, produced by 4 cementitious materials and 3 binder-water ratios of 1 : 4, 1 : 8, and 1 : 12. The proportion of backfill material is shown in Table 4 and the percentage contents of cementing materials are shown in Table 5. Every series 36 cubic samples ($7.07 \times 7.07 \times 7.07\ cm^3$) was made.

The NYL-300 press equipped with microcomputer control and recording system was used to test the uniaxial compressive strength (UCS) of paste backfill test block. The press can be controlled manually and automatically. With control element, the loading mode could be adjusted. In this experiment, displacement control mode with loading rate of 1.5~2 mm/min was set, put the test block in fixture gently, and recorded the test value of destroyed test block. The test data can be automatically recorded and saved by the system. The UCS of 3, 7, 28, and 60 days was measured.

4. Results and Discussion

For same binder-tailing ratio, Figure 4 shows the strength of paste backfill changing with curing ages. For the same curing age, Figure 5 shows the effect of binder-water ratio on the strength of paste backfill.

4.1. Effect of Curing Ages. As shown in Figure 4(a), when the binder-tailing ratio is 1 : 4, the strength of paste backfill increases with increase of curing age. Among five cementing materials, at 3 d curing age, PC32.5 cement shows the best cementing performance with tailing. And the strength of paste backfill with PC32.5 cement as cementing agent is obviously higher than that of other four materials with decreasing order of PC32.5 cement, cementing material I, cementing material II, cementing material III, and finally cementing material IV.

At 7 d curing age, the strength of sample using PC32.5 cement still shows the best bond performance with tailing. As shown in Figure 5, there is strength increase of all samples while the sample using PC32.5 cement increases fastest.

At 28 d curing age, the strength increase is no longer dominated by cementing of tailing and PC32.5 cement instead of cementing of tailing and cementing material I and then cementing material II. The strength of paste backfill with cementing material I and cementing material II is obviously higher than that of other three materials while the strength of backfill with cementing material III and cementing material IV is s till lower than that of backfill with PC32.5 cement. As curve shows, there is dramatic increase compared with that of 3 d curing age and 7 d curing age,

Table 4: Proportion.

Series No.	Tailing-bind ratio b/t	Concentration (%)	Unit mass (kg/m^3) Water	Tailing	Cement	Cement clinker	Water quenching slag	Lead-smelting slag
1	4		538	1108	277	0	0	0
2	8		538	1231	154	0	0	0
3	12		538	1278	106	0	0	0
4	4		535	1100	0	55	220	0
5	8		536	1226	0	31	123	0
6	12		537	1274	0	21	85	0
7	4		535	1101	0	55	176	44
8	8	72	537	1227	0	31	98	25
9	12		537	1275	0	21	68	17
10	4		536	1102	0	55	132	88
11	8		537	1227	0	31	74	49
12	12		537	1275	0	21	51	34
13	4		536	1103	0	55	110	110
14	8		537	1228	0	31	61	61
15	12		537	1276	0	21	43	43

Table 5: Percentage contents of cementing materials.

Binder type	Percentage share of various materials (%) Cement clinker	Water quenching slag	Lead-smelting slag
PC32.5 cement	-	-	-
Cementing material I	20	80	0
Cementing material II	20	64	16
Cementing material III	20	48	32
Cementing material IV	20	40	40

and cementing material I shows the maximum increase slope. The decreasing order is cementing material I, cementing material II, PC32.5 cement, cementing material III, and finally cementing material IV.

At 60 d curing age, cementing material I shows the best cementing performance with tailing and cementing material II takes the second place. The strength of paste backfill with cementing material I and cementing material II is obviously higher than that of other three materials while the strength of paste backfill with cementing material III is a little higher than that of backfill with PC32.5 cement and cementing material IV. As curve shows, the decreasing order of cementing performance with tailing is cementing material I, cementing material II, cementing material III, PC32.5 cement, and finally cementing material IV.

As Figure 4(a) shows, the binder-tailing ratio is 1 : 4, using statistical software to fit test curve, which can obtain logarithmic function relationship between the paste filling body strength δ and curing age ξ when using different varieties of gelled material. As is shown in Table 6, the correlation coefficient range of various expressions is 0.9426 to 0.9882, which means the logarithmic function can fit the two variables properly, and the precision can meet the requirements.

As shown in Figure 4(b), when the binder-tailing ratio is 1 : 8, the strength of paste backfill increases with increase of curing age. Among five cementing materials, at 3 d curing age, PC32.5 cement shows the best cementing performance with tailing. And the strength of paste backfill with PC32.5 cement as cementing agent is obviously higher than that of other four materials with decreasing order of PC32.5 cement, cementing material III, cementing material I, cementing material II, and finally cementing material IV.

At 7 d curing age, PC32.5 cement still shows the best cementing performance with tailing and cementing material III takes the second place. As curve shows, there is strength increase in paste backfill using different cementing materials as cementing agents while PC32.5 cement shows the maximum increase slope. And the decreasing order is PC32.5 cement, then cementing material III, cementing material, cementing material II, and finally cementing material IV.

At 28 d curing age, there is change in cementing of cementing materials and tailing. The cementing material I shows the best cementing performance with tailing and PC3 2.5 cement takes the second place. As curve shows, the decreasing order of cementing performance is cementing material I, PC32.5 cement, cementing material II, cementing material III, and finally cementing material IV.

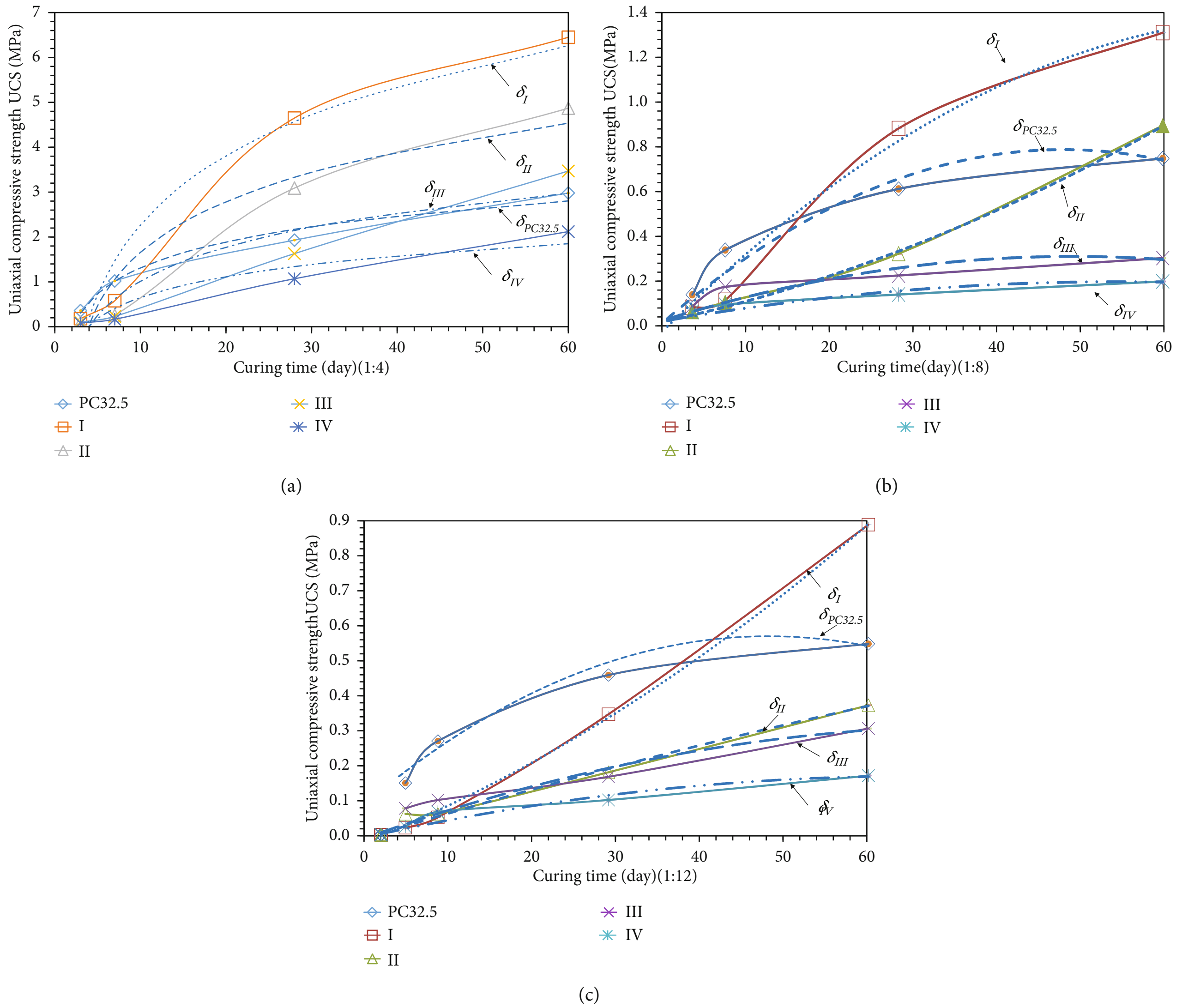

Figure 4: Strength change curve of paste backfill in different curing ages.

As Figure 4(b) shows, the binder-tailing ratio is 1 : 8, using statistical software to fit test curve, which can obtain quadratic polynomial function relationship between the paste filling body strength δ and curing age ξ when using different varieties of gelled material. As is shown in Table 7, the correlation coefficient range of various expressions is 0.9557 to 0.9999, which means the quadratic polynomial function can fit the two variables properly, and the precision can meet the requirements.

As shown in Figure 4(c), at 3 d curing age, among five cementing materials, PC32.5 cement shows the best cementing performance with tailing, then cementing material III, and cementing material II. And the strength of paste backfill with PC32.5 cement as cementing agent is obviously higher than that of other four materials with decreasing order of PC32.5 cement, cementing material III, cementing material II, cementing material IV, and finally cementing material I.

At 7 d curing age, PC32.5 cement still shows the best cementing performance with tailing, then cementing material III, and cementing material IV. As curve shows, the decreasing order of cementing performance is PC32.5 cement, cementing material III, then cementing material IV, cementing material II, and finally cementing material I.

At 28 d curing age, PC32.5 cement still shows the best cementing performance with tailing, then cementing material I, and cementing material II. As curve shows, the decreasing order of cementing performance is PC32.5 cement, cementing material I, cementing material II, cementing material III, and then cementing material IV.

At 60 d curing age, the strength increase is no longer dominated by cementing of tailing and PC32.5 cement instead of cementing of tailing and cementing material I, then PC32.5 cement, and cementing material II. As curve shows, the decreasing order is cementing material I, PC32.5 cement, cementing material II, cementing material III, and finally cementing material IV.

As Figure 4(c) shows, the binder-tailing ratio is 1 : 12, using statistical software to fit test curve, which can obtain quadratic polynomial function relationship between the paste filling body strength δ and curing age ξ when using

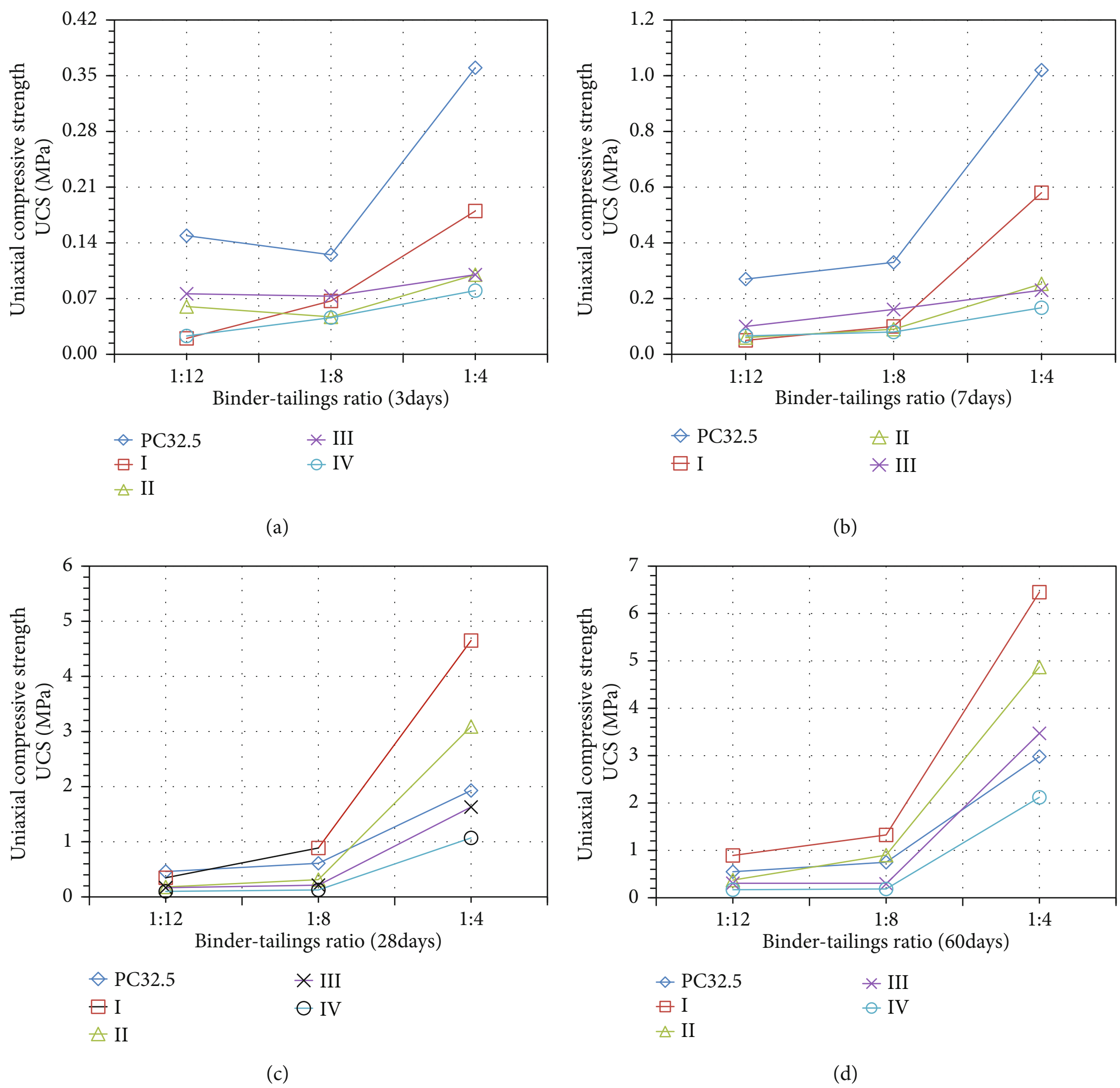

Figure 5: Strength changes with binder-tailing ratio.

Table 6: Functional relationship of UCS and curing age (1 : 4).

Serial number	Mathematical expression	Binder type	Correlation coefficient
1	$\delta_{I} = 2.2354 \ln(\xi) - 2.8868$	I	0.9788
2	$\delta_{II} = 1.6655 \ln(\xi) - 2.2815$	II	0.9701
3	$\delta_{III} = 1.0976 \ln(\xi) - 1.5157$	III	0.9426
4	$\delta_{PC32.5} = 0.8343 \ln(\xi) - 0.6115$	PC32.5	0.9882
5	$\delta_{IV} = 0.6718 \ln(\xi) - 0.8993$	IV	0.9508

different varieties of gelled material. As is shown in Table 8, the correlation coefficient range of various expressions is 0.9776 to 0.9998, which means the quadratic polynomial function can fit the two variables properly, and the precision can meet the requirements.

As shown in Figures 4(a)–4(c), when curing ages are 3 d and 7 d, PC32.5 cement shows the best cementing performance with tailing and the strength of backfill is normal. However, lower strength and late hardening occur in paste backfill using cementing material I, cementing material II, cementing material III, and cementing material IV as binder in earlier period. That is caused by material composition of lead-smelting slag. Generally, the content of SiO_2 in lead-smelting slag is about 24%, and total content of CaO, Al_2O_3, and MgO is about 28%, which is a little high. Small addition of cementing material I and cementing material II has little effect on strength in earlier period but will enhance the strength of paste backfill in later period. With high addition of cementing material III and cementing material IV, the strength of paste backfill is lower and grows slowly with increase of lead-smelting slag in earlier and later period.

4.2. Effect of Binder-Sand Ratios. As Figure 5(a) shows, the strength of paste backfill tends to increase with binder-sand ratio increasing from 1 : 12 to 1 : 8 and 1 : 4 at 3 d curing age, showing the law of strength increases with increase of binder-tailing ratio. Almost all materials follow the law except PC32.5 cement and cementing material II. Using

Table 7: Functional relationship of UCS and curing age (1 : 8).

Serial number	Mathematical expression	Binder type	Correlation coefficient
1	$\delta_{I} = -0.0003\xi^2 + 0.0452\xi - 0.124$	I	0.9958
2	$\delta_{II} = 0.0001\xi^2 + 0.0063\xi + 0.0325$	II	0.9999
3	$\delta_{PC32.5} = -0.0003\xi^2 + 0.0259\xi + 0.0984$	PC32.5	0.9859
4	$\delta_{III} = -5E - 05\xi^2 + 0.0063\xi + 0.0828$	III	0.9557
5	$\delta_{IV} = -2E - 05\xi^2 + 0.0036\xi + 0.0443$	IV	0.9899

Table 8: Functional relationship of UCS and curing age (1 : 12).

Serial number	Mathematical expression	Binder type	Correlation coefficient
1	$\delta_{I} = 7E - 05\xi^2 + 0.0112\xi - 0.0218$	I	0.9998
2	$\delta_{PC32.5} = -0.0002\xi^2 + 0.0168\xi + 0.1266$	PC32.5	0.9902
3	$\delta_{II} = 2E - 05\xi^2 + 0.0044\xi + 0.0385$	II	0.9986
4	$\delta_{III} = 1E - 05\xi^2 + 0.0031\xi + 0.0715$	III	0.9990
5	$\delta_{IV} = -1E - 05\xi^2 + 0.0031\xi + 0.0274$	IV	0.9776

PC32.5 cement and cementing material II as cementing agent, respectively, the strength of backfill with binder-tailing ratio of 1 : 8 is lower than that of backfill with binder-tailing ratio of 1 : 12. As curve shows, at 3 d curing age, the strength of backfill using cement as cementing agent is obviously higher than that of backfill using other cementing materials as agent with different binder-tailing ratios. When the binder-tailing ratio is 1 : 12, the decreasing order of cementing performance is PC32.5 cement, cementing material III, then cementing material II, cementing material IV, and finally cementing material I. When the binder-tailing ratio is 1 : 8, the decreasing order of cementing performance is PC32.5 cement, cementing material III, cementing material I, then cementing material II, and finally cementing material IV. When the binder-tailing ratio is 1 : 4, the decreasing order of cementing performance is PC32.5 cement, cementing material I, cementing material III, then cementing material II, and finally cementing material IV.

As Figure 5(b) shows, the strength of paste backfill increases with binder-tailing ratio increasing from 1 : 12 to 1 : 8 and 1 : 4 at 7 d curing age. As curve shows, at 7 d curing age, the strength of backfill using cement as cementing agent is obviously higher than that of backfill using other cementing materials as agent with different binder-tailing ratios. When the binder-tailing ratio is 1 : 12, the decreasing order of cementing performance is PC32.5 cement, cementing material III, cementing material IV, then cementing material II, and finally cementing material I. When the binder-tailing ratio is 1 : 8, the decreasing order of cementing performance is PC32.5 cement, cementing material III, cementing material I, then cementing material II, and finally cementing material IV. When the binder-tailing ratio is 1 : 4, the decreasing order of cementing performance is PC32.5 cement, cementing material I, cementing material II, then cementing material III, and finally cementing material IV.

As Figure 5(c) shows, the strength of paste backfill increases with binder-tailing ratio increasing from 1 : 12 to 1 : 8 and 1 : 4 at 28 d curing age. As curve shows, at 28 d curing age, when the binder-tailing ratio is 1 : 12, the decreasing order of cementing performance is PC32.5 cement, cementing material I, cementing material II, then cementing material III, and finally cementing material IV. When the binder-tailing ratio is 1 : 8, the decreasing order of cementing performance is cementing material I, PC32.5 cement, cementing material II, then cementing material III, and finally cementing material IV. When the binder-tailing ratio is 1 : 4, the decreasing order of cementing performance is cementing material I, cementing material II, PC32.5 cement, then cementing material III, and finally cementing material IV.

As Figure 5(c) shows, the strength of paste backfill increases with binder-tailings ratio increasing from 1 : 12 to 1 : 8 and 1 : 4 at 60d curing age. As curve shows, at 60d curing age, When the binder-tailings ratio is 1 : 12, the decreasing order of cementing performance is cementing material I, PC32.5 cement, cementing material II, then cementing material III and finally cementing material IV. When the binder-tailings ratio is 1 : 8, the decreasing order of cementing performance is cementing material I, cementing material II, PC32.5 cement, then cementing material III and finally cementing material IV. When the binder-tailings ratio is 1 : 4, the decreasing order of cementing performance is cementing material I, cementing material II, cementing material III, then PC32.5 cement finally cementing material IV.

As shown in Figure 5, test blocks with binder-tailing ratios of 1 : 12 and 1 : 8, there is no obvious law of strength increase to follow at 3 d and 7 d curing ages, while the strength of test blocks with binder-tailing ratio of 1 : 4 is higher than that of blocks with binder-tailing ratios of 1 : 12 and 1 : 8. At 28 d and 70 d, the strength of paste backfill with cementing material I and cementing material II is higher than that of backfill with cementing material III and cementing material IV as cementing agent. And the strength of paste backfill increases gradually with increase of binder-tailing ratio from 1 : 12 to 1 : 8 and 1 : 4. Namely, with higher binder-tailing ratio, cementing materials show good cementing performance with tailing, hydration of active materials is strong, and strength of backfill changes regularly. However, with lower binder-tailing ratio, lower content of cementing materials as well as active materials with weak hydration of active materials, the strength change of backfill shows no obvious pattern, even in disorder.

5. Conclusions

(1) Tests on physical and chemical performance, particle size composition, and intensity ratio of tailing were done in Tongkeng nickel mine. The results show tailing can be prepared into paste backfill slurry and used as filling aggregate due to normal setting and hardening of test blocks and steady strength increase in later period. Test blocks using PC32.5 as cementing material set and hardened normally and the strength of test blocks met the requirements of mining, while the strength of test blocks using substitute for cementing material I, cementing material II, cementing material III, and cementing material IV as cementing material is lower in earlier period and higher than that of test blocks using PC32.5 as cementing material in later period. So the further study on strength of substitute for cement-tailing test block is necessary in future. Meanwhile, the use of smelting slag as much as possible has great significance for environmental protection and sustainable development

(2) When the concentration of paste backfill slurry is 72%, by comparing the strength of test blocks using PC32.5 as cementing agent and test blocks using cementing material I (cement clinker and water quenching slag) as cementing agent, we know that the strength of substitute for cement-tailing backfill test block is lower than that of cement-tailing test block in earlier period (three days and seven days). However, it is higher than that of test blocks using PC32.5 cement as cementing material in 28 days and 60 days, especially when the cement-ratio reaches 1 : 4, and it is almost doubled in later period. Supposing the strength is 1.5 MPa after 28 days, the concentration of paste is 72%, the cement amount will reach 221.73 kg/m^{3,} and substitute for cement amount will reach 188.18 kg/m^3. Namely, the amount of cementing agent could be decreased by 15.13% by using substitute for cement. Supposing the strength is 2.0 MPa, the concentration of paste is 72%, the cement amount will reach 307.21 kg/m^3, and substitute for cement amount will reach 205.23 kg/m^3; then, the amount of cementing agent could be decreased by 33.2%

(3) The substitute for cement is made of water quenching slag and Portland cement clinker. Considering long transportation distance, high purchasing cost, transportation cost, and drying cost of water quenching slag, proportioning, and grinding with cement clinker, the production and processing cost of water quenching slag is expected to be equal to the cost of PC32.5 cement. So if the strength of paste backfill reaches 1.5~2.0 MPa after 28 days, then concentration of paste is 72%, and the amount of cementing agent could be decreased by 15.13~3.2% making use of substitute for cement as cementing agent. Thus, 20% of filling cost could be saved. Replacing water quenching slag with lead-smelting slag, the test results show the activity of lead-smelting slag is far lower than that of water quenching slag owing to its large proportion and low content of CaO in chemical constituents. In other words, as component of substitute for cement, lead-smelting slag will lead to decrease in the strength of paste backfill. As lead-smelting slag still has comprehensive utilization value, no addition or small addition will be economic while meeting the strength requirements simultaneously

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no competing interests.

Authors' Contributions

Daiqiang Deng wrote the main text of the manuscript. Guodong Cao and Yihua Liang collected and analyzed the data. All authors reviewed and commented on the manuscript.

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