

Article

Preparation Process and Performance of Mineral Admixtures Derived from High-Sulfur Lead-Zinc Tailings

Mengyuan Li ^{1,2}, Mingshan Gong ³, Hangkong Li ³, Lijie Guo ^{1,2,*} , Zhong Li ³, Xin Guo ³, Yanying Yin ^{1,2} and Tingting Ren ^{1,2}

¹ BGRIMM Technology Group, Beijing 100160, China; limengyuan@bgrimm.com (M.L.)

² National Centre for International Joint Research on Green Metal Mining, Beijing 102628, China

³ China Railway Resources Group Co., Ltd., Beijing 100039, China

* Correspondence: guolijie@bgrimm.com

Abstract

The large-scale accumulation of high-sulfur lead–zinc tailings poses serious environmental and safety challenges, while the increasing shortage of traditional mineral admixtures such as fly ash and slag highlights the urgent need for sustainable alternatives. This study aims to develop a high-performance mineral admixture using lead–zinc tailings characterized by high SO₃ content and low pozzolanic activity. The effects of four activation routes—mechanical grinding, wet magnetic separation, wet magnetic separation–mechanical grinding, and mechanical grinding–high-reactivity mineral admixture synergistic modification—were systematically compared in terms of tailings fineness, SO₃ reduction, and activity index. The results indicate that single mechanical grinding can achieve the fineness requirement of Grade II admixtures specified in GB/T 1596–2017 (45 μm residue ≤ 30%), but the 28-day strength activity index only reached 58.64%, and the SO₃ content remained above the standard limit. Wet magnetic separation effectively reduced the SO₃ content to below 3.5%, and the combined process yielded a product with an activity index of up to 74.51%. Further improvement was achieved through a “mechanical grinding–high-reactivity mineral admixture synergistic modification” process, incorporating fly ash (FA), ground granulated blast furnace slag (GGBS), and silica fume (SF). Among these, SF exhibited the most pronounced synergistic effect. The optimal mixture, composed of 85.19% ground tailings and 14.81% SF, achieved the highest 28-day activity index of 76.35%. This process enables full utilization of tailings while maintaining a simplified flow, lower energy consumption, and superior product performance. The findings provide a feasible and efficient technological route for the high-value utilization of high-sulfur tailings and contribute to promoting green mining and sustainable resource development.

Keywords: high-sulfur lead-zinc tailings; mineral admixture; pozzolanic activity; synergistic activation process; resource utilization; green mining



Academic Editor: Elsabe Kearsley

Received: 5 November 2025

Revised: 26 November 2025

Accepted: 26 November 2025

Published: 27 November 2025

Citation: Li, M.; Gong, M.; Li, H.; Guo, L.; Li, Z.; Guo, X.; Yin, Y.; Ren, T. Preparation Process and Performance of Mineral Admixtures Derived from High-Sulfur Lead-Zinc Tailings. *Minerals* **2025**, *15*, 1256. <https://doi.org/10.3390/min15121256>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

With the continued exploitation of non-ferrous metal mines, the discharge of lead–zinc tailings has been increasing year by year. The large-scale accumulation of these tailings not only occupies valuable land resources but also poses significant environmental risks, such as acid mine drainage, heavy metal migration, and potential geological hazards [1–3]. In particular, high-sulfur lead–zinc tailings feature complex mineral compositions, elevated SO₃ contents, and low pozzolanic activity, making their utilization more challenging.

Their long-term stockpiling threatens both ecological security and the safety of mining areas [4,5]. At the same time, the availability of traditional mineral admixtures such as fly ash (FA) and ground granulated blast furnace slag (GGBS) is steadily declining. Developing tailings-based alternative mineral admixtures has therefore become an important strategy to alleviate the supply–demand imbalance of supplementary cementitious materials and to promote the high-value utilization of mining solid wastes [6–8].

In the field of building materials, mineral admixtures are indispensable components in cement and concrete systems. They can improve workability, enhance strength and durability, and reduce clinker consumption as well as carbon emissions [9]. Conventional mineral admixtures mainly include industrial by-products such as fly ash, slag powder, and silica fume. However, with the adoption of cleaner production technologies in thermal power plants and industrial restructuring in the steel industry, the supply of high-quality fly ash and slag has become increasingly constrained, urging researchers and engineers to explore new, sustainable substitutes [10,11]. Due to their abundance and chemical compositions similar to conventional admixtures, mine tailings have been recognized as promising supplementary cementitious materials [12,13]. Nevertheless, high-sulfur tailings often contain considerable amounts of pyrite and galena [14,15], resulting in excessive SO_3 content and low reactivity. Such materials generally fail to meet the technical requirements of standards such as GB/T 1596–2017 [16] when used directly. Consequently, how to simultaneously reduce the SO_3 content and activate the latent pozzolanic reactivity of high-sulfur tailings has become a key scientific and engineering challenge for achieving their resource-efficient utilization. Pozzolanic activity refers to the ability of a silicate-rich material to react with calcium hydroxide ($\text{Ca}(\text{OH})_2$) in an alkaline environment to form cementitious compounds such as calcium silicate hydrate (C-S-H) gel, thereby enhancing the strength and durability of cement-based materials. The strength activity index is a standardized metric used to evaluate the pozzolanic performance of mineral admixtures, defined as the ratio of the compressive strength of mortar containing the admixture to that of a pure cement reference mortar, expressed as a percentage.

To address this challenge, extensive research has been carried out on the activation and utilization of mine tailings. Mechanical grinding is one of the most commonly employed physical activation methods, as it can effectively reduce particle size and increase specific surface area, thereby enhancing the reactivity of the material [17,18]. However, this approach has little effect on SO_3 reduction. Wet magnetic separation can selectively remove sulfide minerals such as pyrite, thereby lowering SO_3 content and improving chemical stability, but its contribution to pozzolanic activity is limited [19,20]. In recent years, composite activation and synergistic modification technologies have attracted growing attention. By integrating multiple physical and chemical activation methods, these techniques can simultaneously enhance reactivity and chemical stability. For example, the “wet magnetic separation–mechanical grinding” process combines desulfurization with particle refinement [21,22], while the “mechanical grinding–high-reactivity mineral admixture synergistic modification” process further improves reactivity through heterogeneous pozzolanic interactions [23,24]. These studies have provided valuable insights into the potential use of high-sulfur tailings as mineral admixtures; however, the underlying activation mechanisms and optimal process parameters still require systematic investigation and validation.

In this context, the present study focuses on high-sulfur lead–zinc tailings and systematically investigates four processing routes: mechanical grinding, wet magnetic separation, combined wet magnetic separation–mechanical grinding, and mechanical grinding–high-reactivity mineral admixture synergistic modification. By comparing the SO_3 content, particle characteristics, and strength activity index under different activation conditions,

the study clarifies the mechanisms and performance differences associated with each activation approach. Based on these findings, a suitable preparation process for high-sulfur tailings is proposed. The results provide theoretical guidance and technical support for the high-value utilization of mine tailings and contribute to advancing green mining and solid waste recycling in the construction materials industry.

2. Experiment

2.1. Raw Material

The raw materials employed in this study consisted of high-sulfur lead–zinc tailings, reference cement, ISO standard sand, and high-reactivity mineral admixtures, including ultrafine fly ash (FA), S105-grade ground granulated blast furnace slag (GGBS), and densified silica fume (SF), together with water.

The tailings used in this study were obtained from a lead–zinc concentrator, and their chemical composition is presented in Table 1. The major elements in the tailings are Si, Fe, Ca, and Al. The concentrations of toxic and hazardous elements, such as Pb and As, are extremely low, suggesting that the tailings exhibit good environmental safety and are suitable for use in the preparation of mineral admixtures.

Table 1. Chemical compositions of tailing/%.

Composition	Content	Composition	Content	Composition	Content
Si	34.38	Ti	0.12	Bi	<0.005
Fe	9.36	Zn	0.096	Cd	<0.005
Ca	6.41	Pb	0.089	Co	<0.005
Al	6.21	As	0.074	Li	<0.005
K	3.04	Ba	0.070	Ni	<0.005
S	1.47	Sr	0.042	Sb	<0.005
Mg	0.76	P	0.028	Sn	<0.005
C	0.68	Cu	0.014	V	<0.005
Mn	0.51	Cr	0.0078	LOI	4.23
Na	0.38	Be	<0.005		

Note: LOI—Loss on ignition.

To facilitate the assessment of the tailings' potential for use in cementitious materials, the major elemental composition can be theoretically converted to oxide forms for reference: SiO₂ (73.55%), Al₂O₃ (11.73%), Fe₂O₃ (13.38%), CaO (8.97%), and MgO (1.26%). The high SiO₂ content suggests a potential contribution to strength through a pozzolanic reaction, while the relatively lower contents of Al₂O₃, CaO, and Fe₂O₃ indicate limited inherent pozzolanic activity. It is crucial to note that this theoretical conversion leads to a sum of oxides exceeding 100% due to the complex mineralogy of the tailings, where elements are present in various non-oxide forms. Therefore, the elemental composition in Table 1 provides a more accurate representation of the raw material.

The SO₃ content of the tailings is 3.67 wt%, which exceeds the upper limit of 3.5 wt% for cementitious mineral admixtures specified in GB/T 1596–2017 [16]. Therefore, the material is classified as high-sulfur tailings.

The SO₃ content of 3.67 wt% was derived from the total sulfur content, which was quantitatively determined by X-ray fluorescence (XRF) analysis. The SO₃ value was then calculated using the stoichiometric conversion factor (SO₃ ≈ S × 2.5).

The mineral composition of the tailings is shown in Figure 1. The main mineral phases include quartz, ferropargasite, clinocllore, ferroan clinocllore, sanidine, pyrite, epidote, piemontite, and microperthite. The XRD pattern shows sharp crystalline peaks with a relatively low background hump, suggesting a low amorphous phase content, which

indicates inherently weak pozzolanic activity. Sulfur in the tailings is primarily present in the form of sulfide minerals, such as pyrite (FeS_2).

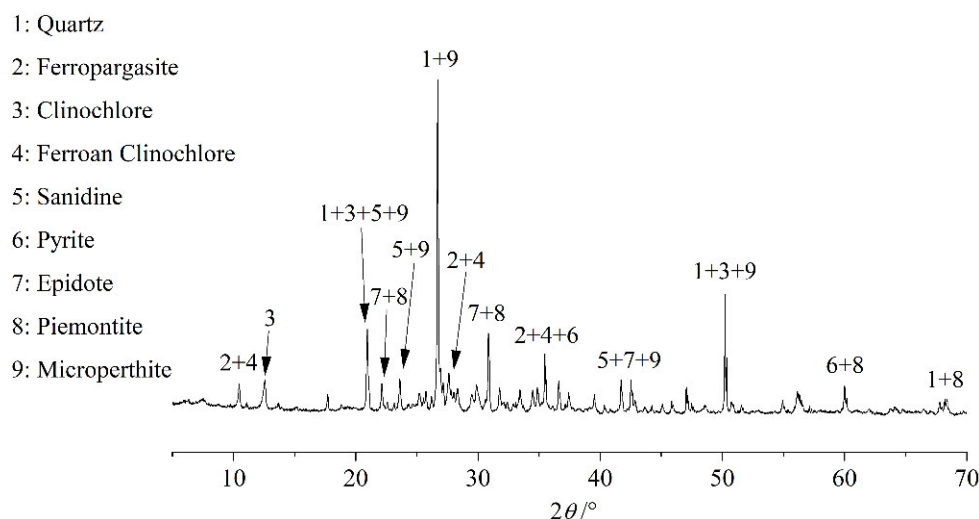


Figure 1. Mineral composition analysis of tailings based on the X-ray diffraction (XRD) method.

The particle size distribution of the tailings, determined by laser diffraction analysis, is illustrated in Figure 2 as a cumulative volume-based curve spanning from 0.4 to 800 μm . The distribution is characterized by key percentile diameters of $d(0.1) = 5.809 \mu\text{m}$, $d(0.5) = 119.840 \mu\text{m}$, and $d(0.9) = 405.399 \mu\text{m}$, representing the particle sizes below which 10%, 50%, and 90% of the total particle volume accumulate, respectively. Furthermore, the cumulative volume fractions of particles finer than 37 μm and 74 μm are 26.84% and 38.20%, respectively, highlighting the significant presence of fine particles in the tailings sample.

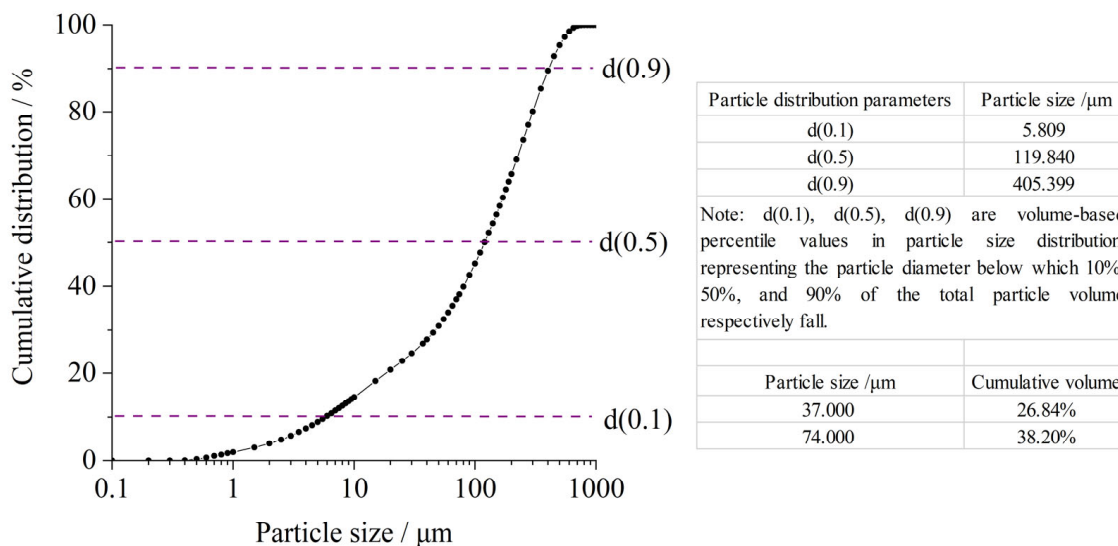


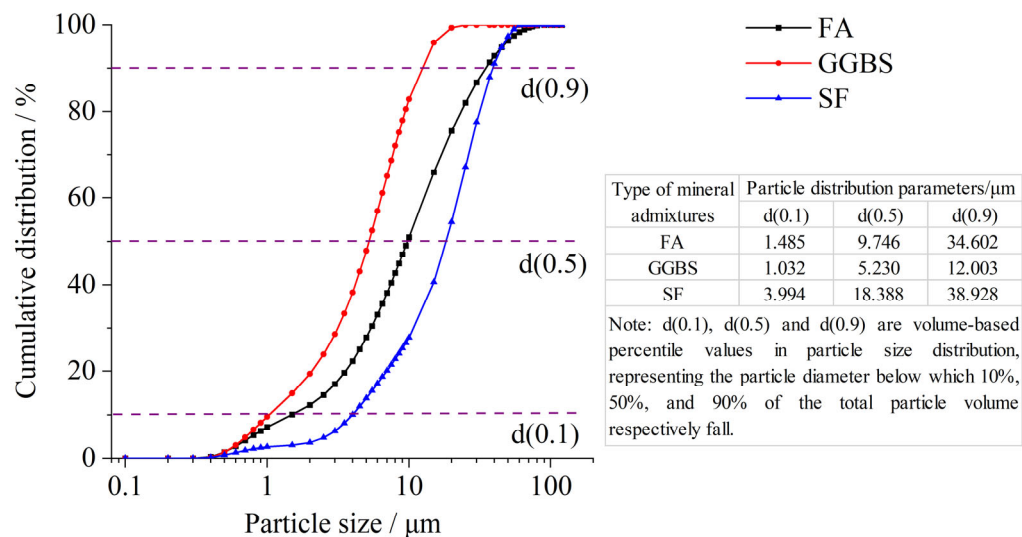
Figure 2. Particle size distribution of tailings.

The chemical compositions of the three highly active mineral admixtures (FA, GGBS, SF) are listed in Table 2, showing that the SO_3 mass fractions of the three mineral admixtures are all below 3.5%. Their particle size distributions are shown in Figure 3. The average particle sizes follow the order: GGBS < FA < SF.

Table 2. Chemical compositions of three highly active mineral admixtures/%.

Composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O _{eq}
FA	55.60	28.00	5.19	4.07	1.13	0.67	3.28
GGBS	14.76	15.99	0.34	38.77	8.31	1.37	1.43
SF	92.99	0.02	0.24	0.60	0.70	0.42	1.04

Note: Na₂O_{eq} represents the sum of Na₂O and 0.658K₂O.

**Figure 3.** Particle size distribution of three highly active mineral admixtures.

2.2. Test Methods

2.2.1. Mechanical Grinding Test

The tailings grinding tests were conducted. Prior to grinding, the samples were dried in an oven at 105 °C for 24 h to remove moisture. Grinding durations were set according to the experimental design. After grinding, a wet sieving test using a 45 μm square-mesh sieve was performed following the requirements of GB/T 1596-2017 [16]. The material retained on the sieve was re-dried for 24 h and weighed, and the residue on the 45 μm sieve was calculated using Equation (1).

$$Sr = (m_2/m_1) \times 100 \quad (1)$$

where Sr is the residue on the 45 μm square-mesh sieve (%), m_1 is the mass of the dry tailings sample before sieving (g), and m_2 is the mass of the dried material retained on the sieve after sieving (g).

2.2.2. Wet Magnetic Separation Test

Sulfur in the tailings is primarily present as pyrite (FeS₂), allowing the separation of high-sulfur and low-sulfur fractions via wet magnetic separation. The tests were conducted using a Slon-100 type high-gradient magnetic separator, with different magnetic field strengths applied for separation. The resulting high-sulfur and low-sulfur tailings were dried at 105 °C to constant weight for subsequent analyses.

2.2.3. Mortar Specimen Preparation and Activity Evaluation

Mortar specimens were prepared and cured according to the standard GB/T 17671-2021 [25], and the 28-day flexural and compressive strengths of the test and reference

mortars were measured (Figures 4 and 5). The strength activity index of the mineral admixtures was calculated using Equation (2).

$$H_{28} = (R/R_0) \times 100 \quad (2)$$

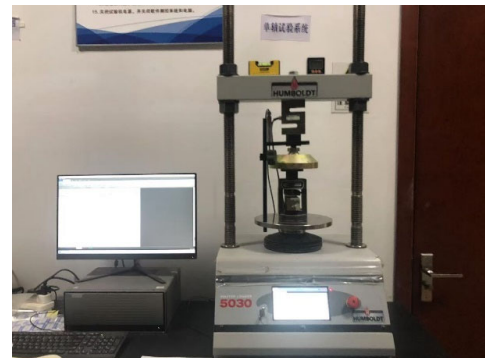
where H_{28} is the 28-day strength activity index (%), R is the 28-day compressive strength of the test mortar (MPa), and R_0 is the 28-day compressive strength of the reference mortar (MPa).



Figure 4. Molded mortar specimens.



(a)



(b)



(c)



(d)

Figure 5. Flexural and compressive strength testing of specimens. (a) Flexural strength; (b) Compressive strength test; (c) Flexural strength test loading head; (d) Compressive strength test loading head.

3. Results and Discussion

3.1. Mechanical Grinding Characteristics of Tailings

3.1.1. Tailings Mechanical Grinding

Mechanical grinding can enhance the reactivity of tailings by refining particle size and increasing specific surface area [17,18]. In this study, the mechanical grinding characteristics of tailings at different grinding durations were systematically investigated using the method described in Section 2.2.1. The grinding times were set at 0, 4, 8, 12, 15, 18, 21, 23, and 25 min. The residues on a 45 μm square-mesh sieve after different grinding durations are shown in Figure 6.

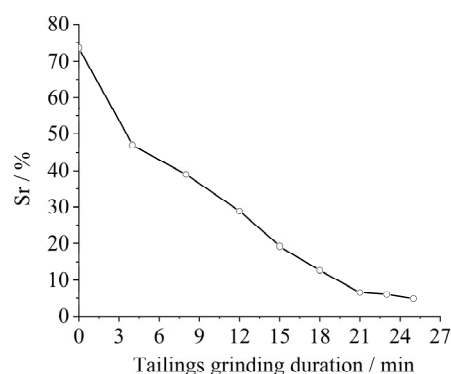


Figure 6. The relationship between grinding duration and the 45 μm sieve residue (Sr).

The results in Figure 6 show that the residue on a 45 μm square-mesh sieve for unground tailings T0 was 73.60%. With increasing grinding time, the 45 μm residue decreased significantly: 47.04% at 4 min, 39.02% at 8 min, 28.84% at 12 min, and further down to 6.56% at 21 min. These results indicate that the high-sulfur lead–zinc tailings possess good grindability. Combined with the fineness requirements in Table 3, it can be seen that a grinding duration of 12 min is sufficient for the tailings to meet the Grade II mineral admixture specification in GB/T 1596–2017 [16] (residue on 45 μm sieve $\leq 30\%$); extending the grinding time further can improve fineness.

Table 3. Fineness requirements for cementitious active blended materials according to standard GB/T 1596–2017 [16].

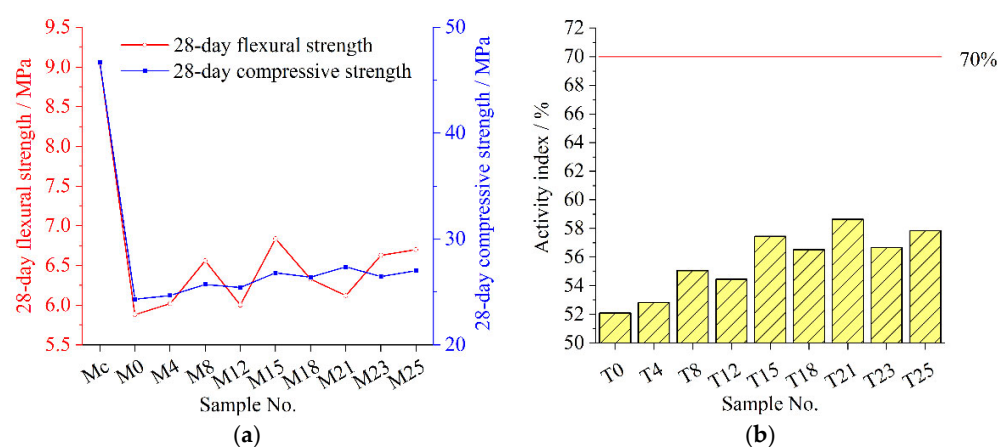
Grade of Cementitious Active Blended Materials	Fineness (Residue on 45 μm Square-Mesh Sieve)/%
Grade I	≤ 12.0
Grade II	≤ 30.0
Grade III	≤ 45.0

3.1.2. Activation Effect of Mechanical Grinding

Based on the results in Section 3.1.1, the mortar strength and activity were evaluated using the method described in Section 2.2.3. The mortar mix proportions for tailings ground for different durations are listed in Table 4. After 28 days of curing, the flexural and compressive strengths were measured, and the strength activity indices were calculated, as shown in Figure 7.

Table 4. Mortar mix proportions for tailings mechanical activation experiments.

Sample No.	Tailings Type	Raw Material Mass			
		Tailings	Reference Cement	Standard Sand	Water
Mc	None	0	450	1350	225
M0	T0	135	315	1350	225
M4	T4	135	315	1350	225
M8	T8	135	315	1350	225
M12	T12	135	315	1350	225
M15	T15	135	315	1350	225
M18	T18	135	315	1350	225
M21	T21	135	315	1350	225
M23	T23	135	315	1350	225
M25	T25	135	315	1350	225

**Figure 7.** Activation performance of tailings with different grinding durations. (a) Flexural strength and compressive strength; (b) Activity index.

As shown in Figure 7, the 28-day flexural and compressive strengths of the tailings mortars generally increase with grinding time. When the grinding duration reached 21 min, the compressive strength of the specimens reached its maximum, corresponding to a strength activity index of 58.64%. These results indicate that mechanical grinding can significantly enhance the reactivity of tailings; however, the improvement is limited, and grinding alone is insufficient to achieve a strength activity index above the standard requirement of 70%.

3.2. Desulfurization Effect of Wet Magnetic Separation

Wet magnetic separation can selectively remove magnetic sulfide minerals, primarily pyrite (FeS_2), from the tailings, thereby effectively reducing the SO_3 content and improving chemical stability [19,20]. In this study, the tailing sample T0 was treated under four magnetic field strengths—5000 Gs, 8000 Gs, 10,000 Gs, and 15,000 Gs—using the method described in Section 2.2.2.

The sulfur content and yield of the high-sulfur and low-sulfur fractions obtained from the wet magnetic separation tests were determined, and the results are presented in Table 5. Compared with the unmagnetically separated tailing T0, which had an SO_3 mass fraction of 3.67%, the SO_3 mass fractions of the low-sulfur fractions obtained after magnetic separation (T0–5000L, T0–8000L, T0–10000L, and T0–15000L) were significantly reduced, indicating that magnetic separation can substantially decrease the SO_3 content in tailings. As the magnetic field strength increased, the SO_3 content in T0–5000L, T0–8000L, T0–10000L, and T0–15000L initially decreased and then stabilized, suggesting that an appropriate increase

in magnetic field strength is effective for reducing SO_3 in tailings. Additionally, the yield of low-sulfur tailings obtained from wet magnetic separation increased with increasing magnetic field strength.

Table 5. Sulfur content and mass yield of tailings after magnetic separation test under different magnetic field strengths.

Sample No.	Mass Fraction of SO_3	Mass of Sample after Magnetic Separation	Mass Yield
T0-5000H	3.87%	348.76	70.48%
T0-5000L	2.10%	146.05	29.52%
T0-8000H	4.67%	273.18	55.65%
T0-8000L	1.70%	217.70	44.35%
T0-10000H	4.94%	321.00	54.80%
T0-10000L	1.42%	264.80	45.20%
T0-15000H	5.84%	264.60	45.84%
T0-15000L	1.50%	312.60	54.16%

Note: 5000H, 8000H, 10000H, and 15000H represent high-sulfur tailings samples separated after wet magnetic separation under magnetic field strengths of 5000 Gs, 8000 Gs, 10,000 Gs, and 15,000 Gs, respectively. Similarly, 5000L, 8000L, 10000L, and 15000L represent low-sulfur tailings samples separated under the corresponding magnetic field strengths. Mass yield represents the mass percentage of the separated fraction (high-sulfur or low-sulfur) relative to the total mass of the original tailings sample before magnetic separation.

It is noteworthy that even at a relatively low magnetic field strength of 5000 Gs, the SO_3 content of the low-sulfur fraction obtained from tailings after magnetic separation meets the upper limit specified in GB/T 1596–2017 [16] for cementitious active blended materials ($\text{SO}_3 \leq 3.5\%$). Therefore, subsequent studies plan to use a magnetic field strength of 5000 Gs for wet magnetic separation of tailings for the following reasons: (1) At 5000 Gs, the SO_3 content of the low-sulfur fraction produced by wet magnetic separation is already well below the maximum limit specified in GB/T 1596–2017 [16] for cementitious active blended materials. (2) The energy consumption at 5000 Gs is lower than that at 8000 Gs, 10,000 Gs, and 15,000 Gs, offering better economic efficiency. (3) Compared with 8000 Gs, 10,000 Gs, and 15,000 Gs, the SO_3 content of the high-sulfur fraction produced at 5000 Gs is the lowest, making the high-sulfur tailings more suitable for backfilling in accordance with GB/T 51450–2022 [26].

3.3. Effect of Combined Activation via Wet Magnetic Separation and Mechanical Grinding

3.3.1. Large-Scale Magnetic Separation Test of Tailings

Based on the results in Section 3.2, approximately 18 kg of tailing T0 were subjected to large-scale magnetic separation at a magnetic field strength of 5000 Gs. The SO_3 content and mass yield of the high-sulfur and low-sulfur tailings are summarized in Table 6. The yield of the low-sulfur tailings was 31.22%, which is generally consistent with the previously reported small-scale test results.

Table 6. Sulfur content and mass yield of tailings after magnetic separation test under a magnetic field strength of 5000 Gs.

Sample No.	Mass Fraction of SO_3	Mass of Sample after Magnetic Separation	Mass Yield
T0-5000H	3.90%	12.4525 kg	68.78%
T0-5000L	2.10%	5.6515 kg	31.22%

Note: 5000H represents the high-sulfur tailings separated after wet magnetic separation under a magnetic field strength of 5000 Gs, while 5000L represents the low-sulfur tailings separated under the same conditions.

3.3.2. Mechanical Grinding Test of the Low-Sulfur Fraction from Wet Magnetic Separation of Tailings

The low-sulfur fraction T0–5000L obtained from wet magnetic separation of tailings was subjected to mechanical grinding, with grinding times set at 0, 4, 8, 12, 16, 20, 24, 28, and 32 min.

The tailings samples subjected to wet magnetic separation at 5000 Gs and subsequent mechanical grinding were wet-sieved, and the residues on a 45 µm square-mesh sieve were calculated, as shown in Table 7. The 45 µm sieve residue of tailing T0–5000L after magnetic separation but without grinding was 81.67%. With increasing grinding time, the 45 µm sieve residue of the magnetically separated tailings continuously decreased. According to Table 3, the 45 µm residue was 33.67% at 12 min, 27.67% at 16 min, and 9.00% at 32 min, corresponding to the fineness standards for Grade III, Grade II, and Grade I mineral admixtures specified in GB/T 1596–2017 [16], respectively. Compared with unmagnetically separated tailings, the grindability of the magnetically separated tailings was slightly reduced, likely due to changes in mineral composition and adjustments in particle size distribution.

Table 7. Residue on a 45 µm square-mesh sieve of tailings T0–5000L after different mechanical grinding durations.

Sample No.	Tailings Grinding Duration	m ₁ /g	m ₂ /g	Sr/%
T0-5000L	0 min	30.00	24.50	81.67%
T4-5000L	4 min	30.00	16.90	56.33%
T8-5000L	8 min	30.00	14.30	47.67%
T12-5000L	12 min	30.00	10.10	33.67%
T16-5000L	16 min	30.00	8.30	27.67%
T20-5000L	20 min	30.00	7.80	26.00%
T24-5000L	24 min	30.00	6.20	20.67%
T28-5000L	28 min	30.00	4.90	16.33%
T32-5000L	32 min	30.00	2.70	9.00%

3.3.3. Investigation of Tailings Activation Performance Based on Mortar Tests

Based on the tailings samples listed in Table 7, mortar mix proportion tests were conducted following the experimental method described in Section 2.2.3, with the mix proportions shown in Table 8.

Table 8. Mortar mix proportions for activation performance experiments of tailings after wet magnetic separation and mechanical grinding.

Sample No.	Tailings Type	Raw Material Mass			
		Tailings	Reference Cement	Standard Sand	Water
Mc	/	0	450	1350	225
M0-5000L	T0-5000L	135	315	1350	225
M4-5000L	T4-5000L	135	315	1350	225
M8-5000L	T8-5000L	135	315	1350	225
M12-5000L	T12-5000L	135	315	1350	225
M16-5000L	T16-5000L	135	315	1350	225
M20-5000L	T20-5000L	135	315	1350	225
M24-5000L	T24-5000L	135	315	1350	225
M28-5000L	T28-5000L	135	315	1350	225
M32-5000L	T32-5000L	135	315	1350	225

After curing the mortar specimens prepared according to the mix proportions in Table 8 for 28 days, the flexural and compressive strengths of the specimens were measured, and the activity indices of the tailings subjected to different mechanical grinding durations were calculated, as shown in Figure 8.

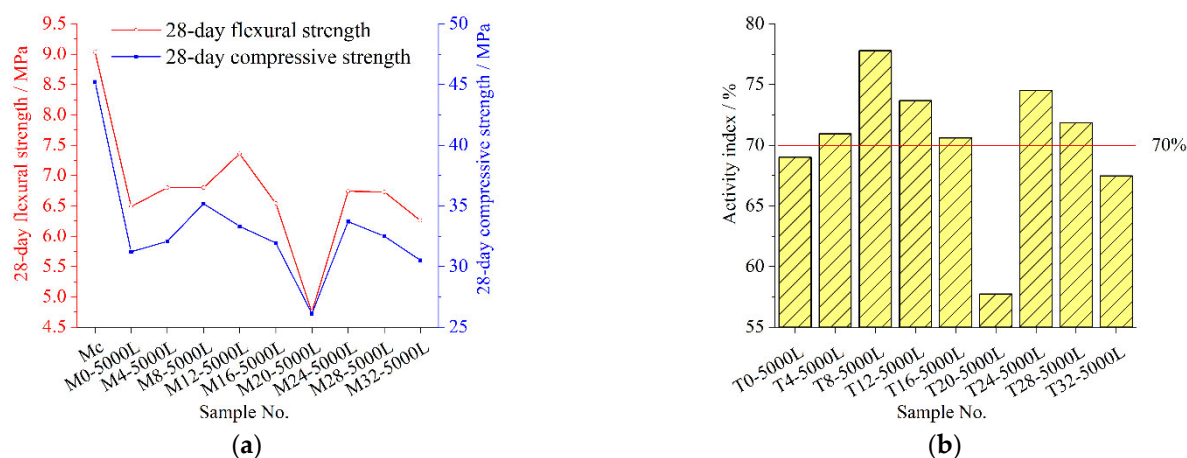


Figure 8. Activation performance of low-sulfur tailings after wet magnetic separation with different grinding durations. (a) Flexural strength and compressive strength; (b) Activity index.

Combined with Figures 7 and 8, it can be seen that the 28-day compressive strength of mortar specimen M0–5000L, prepared from magnetically separated but unground tailing T0–5000L, reached 31.22 MPa, which is significantly higher than the 28-day compressive strength of 24.32 MPa for specimen M0 prepared from unmagnetically separated and unground tailing T0. This indicates that wet magnetic separation can effectively enhance the reactivity of tailings. The underlying mechanism may be that magnetic separation removes surface-encrusted sulfides, making the silico-aluminate active phases more available for hydration and secondary reactions [21,22].

Figure 8 further indicates that the strength activity index of the mineral admixture T0–5000L, prepared from magnetically separated but unground tailing T0, reached 69.01%, which is very close to 70%. The mineral admixtures prepared from magnetically separated and mechanically ground tailings—T4–5000L, T8–5000L, T12–5000L, T16–5000L, T24–5000L, and T28–5000L—all exhibited strength activity indices above 70%, with T8–5000L achieving the highest index of 77.79%.

Based on the results in Tables 6 and 7 and Figure 8, the mineral admixture samples T16–5000L, T24–5000L, and T28–5000L simultaneously meet the Grade II mineral admixture requirements for fineness, SO_3 content, and 28-day strength activity index, with T24–5000L exhibiting the highest 28-day strength activity index of 74.51%.

In summary, wet magnetic separation and mechanical grinding exhibit a clear synergistic effect: the former improves the chemical stability of the raw material through desulfurization, while the latter enhances reactivity via physical activation. The combination of these methods yields a product with both high safety and elevated reactivity.

3.4. Effect of Synergistic Modification by Mechanical Grinding and Highly Active Mineral Admixtures

3.4.1. Minimum Dosage of Highly Active Mineral Admixture

To ensure that the SO_3 content of the tailings-based mineral admixture does not exceed 3.5%, the minimum dosage of different highly active mineral admixtures was calculated based on the data in Table 2, as shown in Table 9. The results indicate that the minimum dosages are 5.67% for FA, 7.39% for GGBS, and 5.23% for SF, demonstrating that only

a relatively small amount of highly active mineral admixture is required to meet the desulfurization requirement.

Table 9. The minimum proportion of high-reactivity mineral admixtures in tailings-based mineral admixtures.

Types of Mineral Admixtures	The Minimum Proportion of High-Reactivity Mineral Admixtures
FA	5.67%
GGBS	7.39%
SF	5.23%

Figure 3 shows the particle size distributions of the three highly active mineral admixtures, with the fractions of particles smaller than 45 µm for FA, GGBS, and SF being 94.91%, 100.00%, and 94.89%, respectively. Accordingly, the residues on a 45 µm square-mesh sieve are 5.09%, 0%, and 5.11% for FA, GGBS, and SF. If the fineness of mechanically ground tailings meets the Grade II cementitious active blended material requirement in GB/T 1596–2017 [16]—i.e., a 45 µm sieve residue not exceeding 30.00%—then mixing any of the highly active mineral admixtures with the tailings in any proportion will result in a composite powder with a 45 µm sieve residue still below 30.00%.

3.4.2. Synergistic Modification of Tailings by Mechanical Grinding and Highly Active Mineral Admixtures

The study selected tailing T12 for synergistic modification with highly active mineral admixtures. Tailing T12 was unmagnetically separated, mechanically ground for 12 min, and had a 45 µm sieve residue of 28.84%, meeting the Grade II cementitious active blended material requirements in GB/T 1596–2017 [16]. Compared with tailings ground for more than 12 min, T12 exhibited the lowest strength activity index of 54.45%, but the energy consumption was minimal and the efficiency was highest. After uniformly mixing tailing T12 with different types of highly active mineral admixtures, mortar tests were conducted. The mix proportions for the mortar specimens prepared using the mechanical grinding–highly active mineral admixture synergistic modification method are listed in Table 10.

Table 10. Mortar mix proportions for tailings mechanical–chemical composite activation experiments.

Sample No.	Highly Active Mineral Admixture		Tailings T12	Mass of Other Raw Materials		
	Type	Mass	Proportion	Reference Cement	Standard Sand	Water
Mc	/	0	/	450	1350	225
M12	/	0	0%	315	1350	225
M12-FA10	FA	10	7.41%	315	1350	225
M12-FA15	FA	15	11.11%	315	1350	225
M12-FA20	FA	20	14.81%	315	1350	225
M12-FA25	FA	25	18.52%	315	1350	225
M12-GGBS10	GGBS	10	7.41%	315	1350	225
M12-GGBS15	GGBS	15	11.11%	315	1350	225
M12-GGBS20	GGBS	20	14.81%	315	1350	225
M12-GGBS25	GGBS	25	18.52%	315	1350	225
M12-SF10	SF	10	7.41%	315	1350	225
M12-SF15	SF	15	11.11%	315	1350	225
M12-SF20	SF	20	14.81%	315	1350	225
M12-SF25	SF	25	18.52%	315	1350	225

Note: The proportion of highly active mineral admixture refers to its content in the tailings-based mineral admixture, i.e., the mass of the highly active mineral admixture divided by the total mass of the highly active mineral admixture and tailings T12.

After curing the mortar specimens prepared according to the mix proportions in Table 10 for 28 days, the flexural and compressive strengths of the specimens were measured, and the strength activity indexes of the mineral admixtures were calculated, as shown in Figure 9.

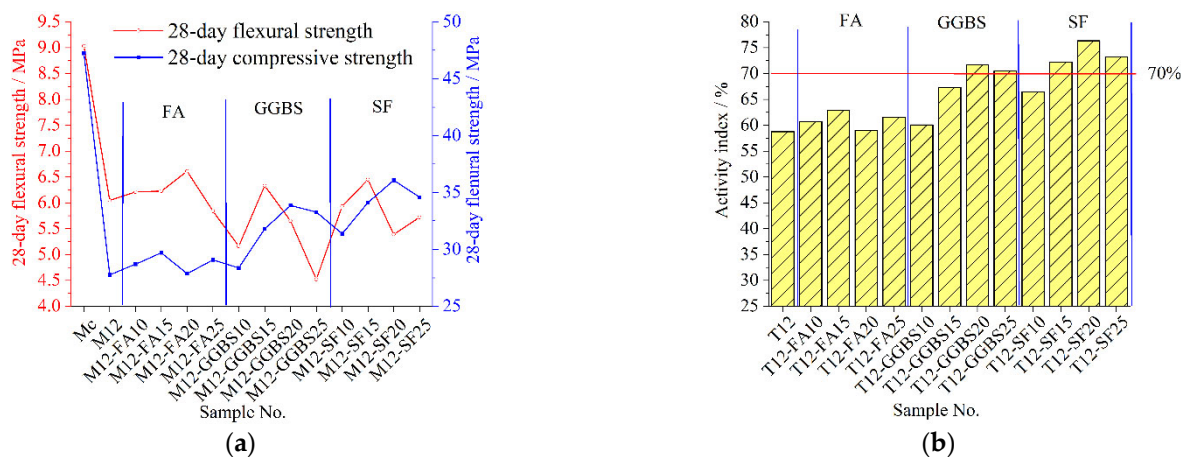


Figure 9. Activation performance of tailings-based mineral admixtures prepared by mechanical grinding and synergistic modification with highly active mineral admixtures. (a) Flexural strength and compressive strength; (b) Activity index.

Figure 9 indicates that among the mineral admixtures prepared by synergistic modification of tailings T12 with highly active mineral admixtures, SF produced the most significant improvement in compressive strength and strength activity index, followed by GGBS, while FA showed the least effect. The primary reason is that SF is rich in high-specific-surface-area amorphous SiO_2 , which can undergo pozzolanic reactions with $\text{Ca}(\text{OH})_2$ in an alkaline environment, generating more C–S–H gel and significantly enhancing cementitious strength and density. GGBS contributes reactive Si–Al components and participates in hydration under alkaline activation, also improving system reactivity. In contrast, FA’s reactivity depends on its amorphous content and particle size distribution, resulting in relatively moderate overall activity [27–29].

Comprehensive analysis indicates that the mineral admixtures M12–GGBS20, M12–GGBS25, M12–SF15, M12–SF20, and M12–SF25 simultaneously meet the Grade II cementitious active blended material requirements in GB/T 1596–2017 [16] for fineness, SO_3 content, and 28-day strength activity index. Among them, mineral admixture M12–SF20 exhibits the highest 28-day strength activity index of 76.35%.

Overall, the “mechanical grinding–highly active mineral admixture synergistic modification” approach can significantly enhance the reactivity of tailings-based admixtures while ensuring fineness and chemical stability. Through heterogeneous blending and secondary hydration reactions, this method demonstrates superior overall performance compared with either single mechanical grinding or the “magnetic separation–grinding” process.

4. Production Process of Mineral Admixtures

4.1. Production Process of Mineral Admixtures via Combined Wet Magnetic Separation and Mechanical Grinding Activation Using High-Sulfur Lead–Zinc Tailings

Based on the results in Section 3.4, the mineral admixtures T16–5000L, T24–5000L, and T28–5000L simultaneously meet the Grade II cementitious active blended material requirements in GB/T 1596–2017 [16] for fineness, SO_3 content, and 28-day strength activity index. The production process for this type of mineral admixture is illustrated in Figure 10.

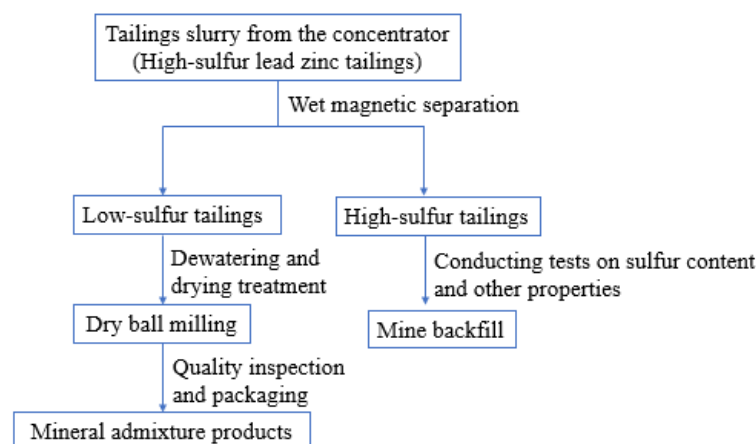


Figure 10. Production process flow of mineral admixtures prepared from high-sulfur lead–zinc tailings via wet magnetic separation and mechanical grinding composite activation.

The detailed production process is as follows:

- (1) Wet magnetic separation: High-sulfur lead–zinc tailings are subjected to wet magnetic separation using a wet magnetic separator. The sulfur content in the separated low-sulfur and high-sulfur fractions is measured. The SO_3 content of the low-sulfur fraction should be below 3.5% to allow further use in mineral admixture production, while the elemental sulfur content of the high-sulfur fraction should be below 8% to meet underground backfilling requirements.
- (2) Dewatering and drying: The low-sulfur tailings fraction meeting the SO_3 requirement is dewatered and dried using a tailings filter press and tailings dryer to remove water content.
- (3) Mechanical grinding: The dewatered and dried low-sulfur tailings are mechanically ground in a ball mill to the desired fineness. After quality inspection and packaging, the mineral admixture product is obtained.

4.2. Production Process of Mineral Admixtures via Mechanical Grinding–Highly Active Mineral Admixture Synergistic Modification Using High-Sulfur Lead–Zinc Tailings

Based on the results in Section 3.4, the mineral admixtures M12–GGBS20, M12–GGBS25, M12–SF15, M12–SF20, and M12–SF25 simultaneously meet the Grade II cementitious active blended material requirements in GB/T 1596–2017 [16] for fineness, SO_3 content, and 28-day strength activity index. The production process for this type of mineral admixture is illustrated in Figure 11.

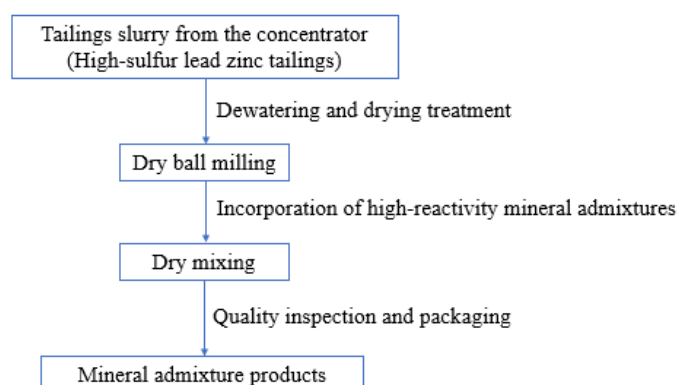


Figure 11. Production process flow of mineral admixtures prepared from tailings via mechanical grinding and synergistic modification with highly active mineral admixtures.

The detailed production process is as follows:

- (1) Dewatering and drying: Tailings slurry is dewatered and dried using a tailings filter press and tailings dryer to remove water.
- (2) Mechanical grinding: The dewatered and dried tailings are mechanically ground in a ball mill to the required fineness.
- (3) Synergistic modification with highly active mineral admixtures: An appropriate amount of highly active mineral admixture (GGBS or SF) is added to the mechanically ground tailings and thoroughly mixed in a dry-mixing machine. After quality inspection and packaging, the tailings-based mineral admixture is obtained.

4.3. Analysis of Optimal Production Process

A comprehensive comparison of the advantages and disadvantages of the two production processes is summarized in Table 11. It can be clearly seen that, compared with the mechanical grinding–highly active mineral admixture synergistic modification process, the wet magnetic separation–mechanical grinding activation process for tailings-based mineral admixture, although not requiring additional activator costs, has several drawbacks: the maximum reactivity of the produced mineral admixture is lower; additional wet magnetic separators must be procured, which entails ongoing energy consumption and periodic maintenance costs; the yield of low-sulfur tailings separated by wet magnetic separation is low, while the separated high-sulfur fraction has higher sulfur content and higher yield, which may adversely affect underground backfilling. Therefore, the optimal production process for high-sulfur lead–zinc tailings is the mechanical grinding–highly active mineral admixture synergistic modification method.

Table 11. Comparative analysis of production processes for tailings-based mineral admixtures.

Production process	Wet magnetic separation–mechanical grinding	Mechanical grinding–synergistic modification with highly active mineral admixtures
Maximum activity index of the product	The mineral admixture T24–5000L exhibits the highest activity, reaching 74.51%.	The mineral admixture M12–SF20 exhibits the highest activity, reaching 76.35%.
Main process equipment	Wet magnetic separator Tailings dewatering filter press Tailings dryer Ball mill	Tailings dewatering filter press Tailings dryer Ball mill Dry-mixing mixer
Highly active mineral admixture	None	GGBS or SF
Impact on other production processes	High-sulfur tailings produced by wet magnetic separation have higher sulfur content and yield, which can easily affect the quality of mine backfill.	No impact.
Tailings utilization rate	Taking mineral admixture T24–5000L as an example, after wet magnetic separation, the yield of low-sulfur tailings available for mineral admixture preparation is only 31.22% (see Table 6).	All tailings can be used 100% for the production of mineral admixtures.

5. Conclusions

Based on the results of this study, the following conclusions can be drawn:

- (1) Mechanical grinding can effectively refine tailings particles, optimize particle size distribution and specific surface area, thereby enhancing their potential pozzolanic activity. When the grinding time reaches at least 12 min, the 45 μm sieve residue of the tailings is below 30%, and the 28-day strength activity index can reach up to 58.64%.

While mechanical grinding alone provides good activation, it is insufficient to achieve high-grade reactivity.

- (2) Wet magnetic separation of high-sulfur lead–zinc tailings can efficiently remove high-sulfur fractions, reducing the SO₃ content from 3.67% to 2.10%, thereby meeting the Grade II mineral admixture limit in GB/T 1596–2017 [16] and laying a foundation for subsequent activation.
- (3) The “wet magnetic separation–mechanical grinding” combined activation process enables synergistic optimization of desulfurization and activation. The low-sulfur tailings obtained after magnetic separation and subsequent grinding exhibit superior fineness and reactivity compared with solely ground samples, with a 28-day strength activity index reaching 74.51%, meeting Grade II mineral admixture standards. This process significantly enhances reactivity while maintaining SO₃ control.
- (4) Incorporating highly active mineral admixtures can further improve the reactivity and chemical stability of tailings. Silica fume shows the most pronounced activation effect; at a dosage of 14.81%, the 28-day strength activity index reaches 76.35%. The mechanism involves the secondary reaction between amorphous SiO₂ and Ca(OH)₂, generating additional C–S–H gel and improving the compactness of the cementitious structure.
- (5) The study identifies the mechanical grinding–highly active mineral admixture synergistic modification process as the optimal production method. The resulting mineral admixture products exhibit low SO₃ content, appropriate fineness, and high reactivity, with no adverse impact on underground backfilling. Tailings utilization can reach 100%, achieving reduction, detoxification, and value-added reuse of tailings. This process has significant engineering implications for promoting green mining and the circular utilization of mineral waste.

Author Contributions: Conceptualization, M.L., M.G., H.L., L.G. and Z.L.; Methodology, M.L., M.G., H.L., Z.L. and X.G.; Software, M.L., Y.Y. and T.R.; Validation, L.G. and X.G.; Formal analysis, M.L., X.G., Y.Y. and T.R.; Investigation, M.L., M.G., H.L., L.G. and X.G.; Resources, M.G., H.L., L.G., Z.L. and X.G.; Data curation, M.L., X.G., Y.Y. and T.R.; Writing—original draft, M.L.; Writing—review and editing, M.L.; Visualization, M.L., Y.Y. and T.R.; Supervision, M.G., H.L., L.G. and Z.L.; Project administration, M.L., M.G., H.L., L.G. and Z.L.; Funding acquisition, M.L., M.G., H.L. and L.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (No. 52274122) and the Mining and Metallurgy Yingfan Fund of BGRIMM Technology Group (No. 09-2410).

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: Mengyuan Li, Lijie Guo, Yanying Yin and Tingting Ren are employees of BGRIMM Technology Group. Mingshan Gong, Hangkong Li, Zhong Li and Xin Guo are employees of China Railway Resources Group Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Li, J.; Chen, L.; Li, B.; Chen, B. Modification of magnesium phosphate cement by lead-zinc tailings: Dual benefits in mechanical strength enhancement and leaching toxicity reduction. *Constr. Build. Mater.* **2025**, *497*, 143906. [\[CrossRef\]](#)
2. Biglari, H.; Mousavi, S.M.; Yaghmaeian, K.; Dehghani, M.H.; Nodehi, R.N.; Nazmara, S.; Alimohammadi, M. Comprehensive health and environmental risk assessment of zanzan lead-zinc hydrometallurgy tailings. *Results Eng.* **2025**, *26*, 105160. [\[CrossRef\]](#)

3. Zhou, J.; Liu, Z.; Li, Z.; Xie, R.; Jiang, X.; Cheng, J.; Chen, T.; Yang, X. Heavy metals release in lead-zinc tailings: Effects of weathering and acid rain. *J. Hazard. Mater.* **2025**, *483*, 136645. [\[CrossRef\]](#)
4. Liu, Y.; Wu, S.; You, F.; Saha, N.; Chan, T.-S.; Huang, L. Attenuation of pollution risks in sulfidic lead-zinc tailings through accelerating weathering of sulfides by indigenous acidithiobacillus consortia. *Chem. Geol.* **2025**, *683*, 122765. [\[CrossRef\]](#)
5. Wang, Z.; Wu, A.; Wang, S.; Zhao, Y. From performance to mechanism: Analysis of controlling strength attenuation of high-sulfur lead-zinc tailings cemented paste backfill. *Miner. Eng.* **2025**, *225*, 109233. [\[CrossRef\]](#)
6. Tian, B.; Wang, N.; Ye, R.; Li, X.; Zhang, B. The utilization of wet grinding copper tailing for preparing ultra-high performance concrete. *Next Mater.* **2025**, *9*, 101085. [\[CrossRef\]](#)
7. Hou, S.; Guo, Y.; Sun, J.; Jiang, J.; Gao, H.; Liu, J. Prospect of gold tailings as a new mineral admixture: Effect on hydration, pore structure and mechanical properties of concrete, *Mater. Today Sustain.* **2025**, *29*, 101078. [\[CrossRef\]](#)
8. Yalley, P.P.; Kankam, C.K. Compressive, flexural and corrosion permeability resistance properties of concrete with bauxite tailing as supplementary mineral admixtures. *Sci. Afr.* **2022**, *18*, e01409. [\[CrossRef\]](#)
9. Jindal, B.B. Investigations on the properties of geopolymer mortar and concrete with mineral admixtures: A review. *Constr. Build. Mater.* **2019**, *227*, 116644. [\[CrossRef\]](#)
10. Zheng, Z.; Tan, H.; He, X.; Su, Y.; Wang, Y.; Yang, J.; Li, Y. Physical-chemical characterization and application research of copper tailings with wet-grinding activation for use as supplementary cementitious material. *Constr. Build. Mater.* **2025**, *489*, 142077. [\[CrossRef\]](#)
11. Zhao, Z.; Ji, C.; Wang, J.; Zhu, L.; Wang, D.; Tošić, N. Investigation of gold mine tailings as supplementary cementitious material: Performance and carbon footprint. *J. Cleaner Prod.* **2025**, *518*, 145933. [\[CrossRef\]](#)
12. Zhang, B.; Muhammad, F.; Yu, T.; Fahimzadeh, M.; Hassan, M.A.S.; Liang, J.; Ning, X.; Yuan, P. Harnessing iron tailings as supplementary cementitious materials in limestone calcined clay cement (LC3): An innovative approach towards sustainable construction. *Constr. Build. Mater.* **2024**, *453*, 139111. [\[CrossRef\]](#)
13. Yao, Z.; Kashani, A.; Rawal, A.; Song, H.; Kim, T. Heat-induced phase transitions in mining tailings to create alternative supplementary cementitious materials. *Resour. Conserv. Recycl.* **2024**, *210*, 107818. [\[CrossRef\]](#)
14. He, Q.; Cao, S.; Yilmaz, E. Characterizing mechanical and multiscale porosity features of cementitious high sulfur tailings backfill using CT technology. *Process Saf. Environ. Prot.* **2025**, *194*, 858–872. [\[CrossRef\]](#)
15. Huang, S.; Pi, Z.; Cai, C.; Li, H. Utilization of high-sulfur iron ore tailings in cement mortar by considering the influence of curing temperature and tailing content. *J. Build. Eng.* **2023**, *74*, 106826. [\[CrossRef\]](#)
16. GB/T 1596–2017; Fly Ash Used for Cement and Concrete. National Standard of the People's Republic of China: Beijing, China, 2017.
17. Gu, X.; Liu, B.; Li, Z.; Wang, H.; Liu, J.; Nehdi, M.L.; Zhang, Y. Mechanical grinding kinetics and particle packing novel characterization of iron ore tailings as inert filler for cement mortar. *J. Build. Eng.* **2023**, *78*, 107558. [\[CrossRef\]](#)
18. Yao, G.; Liu, Q.; Wang, J.; Wu, P.; Lyu, X. Effect of mechanical grinding on pozzolanic activity and hydration properties of siliceous gold ore tailings. *J. Cleaner Prod.* **2019**, *217*, 12–21. [\[CrossRef\]](#)
19. Zhang, H.; Zeng, J.; Ji, Y.; Chen, L. Separation characteristics and magnetic agglomeration behavior in wet low-intensity magnetic separation process: Based on CFD-DEM-FEM. *Powder Technol.* **2026**, *469 Pt 2*, 121794. [\[CrossRef\]](#)
20. Bazin, C.; Sista, R.; Légaré, B.; Caron, J.; Lavoie, F. Investigation of the effect of mineral composition and size on particle separation in wet low and high intensities magnetic separators: An industrial case. *Miner. Eng.* **2024**, *218*, 109003. [\[CrossRef\]](#)
21. Duarte, M.S.; Almada, B.S.; Santos, W.J.D.; Bessa, S.A.L.; da Silva Bezerra, A.C.; Aguilar, M.T.P. Influence of mechanical treatment and magnetic separation on the performance of iron ore tailings as supplementary cementitious material. *J. Build. Eng.* **2022**, *59*, 105099. [\[CrossRef\]](#)
22. Zhang, L.; Jiang, T.; Guo, X.-Y.; Tian, Q.-H.; Zhong, S.-P.; Dong, L.; Qin, H.; Liu, Z.-W.; Makuza, B. Sustainable processing of gold cyanide tailings: Reduction roasting, mechanical activation, non-cyanide leaching, and magnetic separation. *Hydrometallurgy* **2023**, *217*, 106028. [\[CrossRef\]](#)
23. Li, Y.; Dang, F.; Zhou, M.; Zhang, Y. Activity characteristics and activation mechanism of molybdenum tailings under mechanical, mechano-thermal, mechano-chemical, and mechano-thermal-chemical activation. *Constr. Build. Mater.* **2025**, *463*, 140109. [\[CrossRef\]](#)
24. Yang, Y.; Yang, Z.; Cheng, Z.; Zhang, H. Effects of wet grinding combined with chemical activation on the activity of iron tailings powder. *Case Stud. Constr. Mat.* **2022**, *17*, e01385. [\[CrossRef\]](#)
25. GB/T 17671-2021; Test Method of Cement Mortar Strength (ISO Method). National Standard of the People's Republic of China: Beijing, China, 2021.
26. GB/T 51450-2022; Technology Standard for Backfill Engineering in Metallic and Non-Metallic Mines. National Standard of the People's Republic of China: Beijing, China, 2022.
27. Yoon, J.; Jafari, K.; Tokpatayeva, R.; Peethamparan, S.; Olek, J.; Rajabipour, F. Characterization and quantification of the pozzolanic reactivity of natural and non-conventional pozzolans. *Cem. Concr. Compos.* **2022**, *133*, 104708. [\[CrossRef\]](#)

28. Xu, W.; Lo, T.Y.; Wang, W.; Ouyang, D.; Wang, P.; Xing, F. Pozzolanic reactivity of silica fume and ground rice husk ash as reactive silica in a cementitious system: A comparative study. *Materials* **2016**, *9*, 146. [[CrossRef](#)] [[PubMed](#)]
29. Li, G.; Zhou, C.; Ahmad, W.; Usanova, K.I.; Karelina, M.; Mohamed, A.M.; Khallaf, R. Fly ash application as supplementary cementitious material: A review. *Materials* **2022**, *15*, 2664. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.