

Influence of Mechanochemical Effects on The Strength Activity of Micro-Powder Derived from Multi-Source Solid Waste

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ABSTRACT

Driven by China emission peak and carbon neutrality goals, the efficient utilization of industrial solid wastes to develop low-carbon cementitious materials has become a critical research focus. This study investigates the activity enhancement mechanisms and synergistic effects of ultrafine powders derived from multi-source solid wastes (steel slag, slag, and lead-zinc tailings) in western and central Fujian Province through mechanochemical technology. Experiments compared the specific surface area, 7-day and 28-day strength activity indices of single and mixed materials under varying grinding durations, while revealing their hydration synergistic mechanisms. Results indicate that among single materials, slag exhibited optimal activity, achieving a specific surface area of 3.18 m²/g after 60 min of grinding, with 7-day and 28-day strength activity indices of 121.32% and 113.78%, respectively. The activities of steel slag and tailings were significantly lower than those of slag, but extending grinding time increased early activity to 40%. For mixed materials, slag-dominated systems demonstrated superior performance: the 28-day activity reached 89.87% after two-stage grinding (slag + steel slag), while three-stage grinding (slag-tailings-steel slag) achieved a remarkable 28-day activity index of 144.02%, attributed to the pore-filling effect of slag and chemical synergy between components. SEM and XRF analyses revealed that the dense structure and optimized particle gradation of mixed powders were key to activity enhancement, with mechanochemistry-induced amorphization, lattice distortion, and surface energy elevation further promoting hydration. The study confirms that graded grinding sequences and proportioning of multi-source solid wastes significantly influence activity, and prioritizing slag grinding maximizes its pozzolanic effect. These findings provide theoretical and technical pathways for efficient industrial solid waste recycling, facilitating the low-carbon transition in the building materials industry.

INTRODUCTION

"Carbon peaking and carbon neutrality" represent an inevitable pathway for China's green development. Policy documents such as the Action Plan for Carbon Peaking Before 2030 issued by the State Council of China and the Implementation Plan for Carbon Peaking in the Building Materials Industry jointly released by multiple ministries explicitly emphasize the need to advance carbon peaking in the building materials sector, encouraging enterprises to accelerate solid waste utilization and develop novel low-carbon cementitious materials Zhang et al. (2019), Zhang et al. (2020) Metal tailings in west-central Fujian Province

are highly concentrated, and Fujian Sansteel Group, located in this region, generates millions of tons of solid waste annually, including slag and steel slag, in cities such as Sanming, Quanzhou, and Luoyuan. Persistent challenges such as high output, massive stockpiling, low utilization rates, and disposal difficulties for metal tailings and steel slag remain unresolved, with stockpiling occupying land and causing environmental pollution. Against the backdrop of the central government's prioritization of carbon peaking and Fujian Province's inclusion of green economy as one of the "four engines" for high-quality development Zhang et al. (2020) there is

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an urgent demand for efficient, synergistic, and safe treatment solutions for industrial solid wastes like steel slag, slag, and metal tailings widely distributed in west-central Fujian. Mechanochemistry, which utilizes mechanical energy input to induce crystal structure reorganization, increased surface-active sites, and chemical bond breakage/reconstruction, serves as a core technology for enhancing the resource efficiency of industrial solid wastes.

Its mechanisms can be categorized as follows: (1) Physical modification: Particle refinement and pore structure optimization improve the cementitious activity of steel slag, slag, and 66 lead-zinc tailings Chen et al.(2024),Wu et al.(2024); (2) Chemical activation: Generation of amorphous phases (e.g., increasing glass phase content in slag from 50% to 80%) and mineral phase transformation, such as the conversion of heavy metal sulfides to oxides in lead-zinc tailings and the transition of C_2S (dicalcium silicate) to β - C_2S during steel slag ball milling, reducing free CaO content to below 1.5% Zhang et al. (2002), Li et al.(2022),significantly enhancing volume stability; (3) Energy storage: Lattice distortion-induced internal energy accumulation (activation energy reduced by 30%-50%) provides driving force for subsequent reactions Kumar et al.(2021).

Studies have shown that slag, steel slag, and metal tailings exhibit compositional complementarity, and their combined use outperforms individual applications, garnering increasing attention in recent years. Liu Q et al. (2019) systematically analyzed the pathways for preparing green building materials such as geopolymers and ceramic foams from lead-zinc tailings. Wen JB et al. (2008) investigated the activation effect of mechanochemical methods on steel slag, where high-energy grinding modifies its crystal structure to enhance both amorphous degree and reactivity. Gao S et al. (2002) employed high-energy ball milling technology to conduct mechanochemical activation on three types of slag, examining variations in particle size, density, and compressive strength. The optimal ball milling duration is identified as 2–4 hours. Chen MM et al. (2014) prepared Portland cement clinker by substituting iron powder and clay with steel slag and lead-zinc tailings, respectively. Li GY et al. (2019) demonstrated that replacing cement with steel slag at $\leq 20\%$ or co-blending steel slag and slag at $\leq 30\%$ did not significantly compromise concrete strength. Huang H et al. (2021) formulated a composite admixture by combining coarse steel slag, fine slag, and commercial Portland cement, achieving 7-day and 28-day compressive strength activity indices of 94% and 101%, respectively. Li BX et al. (2013) tested the effects of multi-stage grinding durations, material ratios, and grinding aids on the particle size distribution and paste strength of iron tailings-slag composite powders. An SH et al. (2023) found that co-blended slag and iron tailing powders exhibited synergistic effects during hydration, notably

improving pore structure in hardened specimens and regulating the proportions of Aft crystalline products and C-(A)-S-H gels, thereby enhancing volume stability. Previous research has seldom addressed the influence of mechanochemistry on the strength activity of ultrafine powders derived from multi-source solid wastes such as slag-steel slag-lead-zinc tailings. Therefore, this study aims to investigate the effects of mechanochemical treatment on the fineness and strength activity indices of these multi-source solid waste ultrafine powders, further elucidating the underlying mechanisms.

MATERIAL AND METHODS

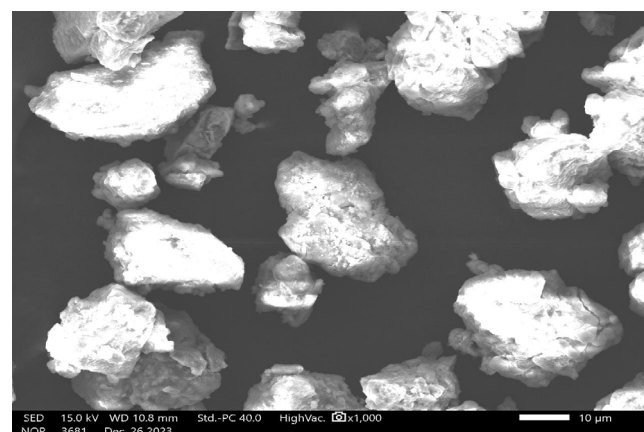
Raw Material Preparation

The lead-zinc tailing micropowder used in the experiments was produced by Fujian Youtairen Environmental Technology Co., Ltd., while the slag and steel slag were finely ground products from Sansteel Minguang Group Co., Ltd. The apparent morphology, SEM microstructure, and XRF compositional analysis results of the lead-zinc tailings, slag, and steel slag are shown in Figures 1–3 and Table 1. The specific surface areas of the lead-zinc tailing micropowder, slag, and steel slag were 450 m²/kg, 520 m²/kg, and 410 m²/kg, respectively.

Figure 1: Lead-zinc tailing micropowder and its SEM image ($\times 1000$)

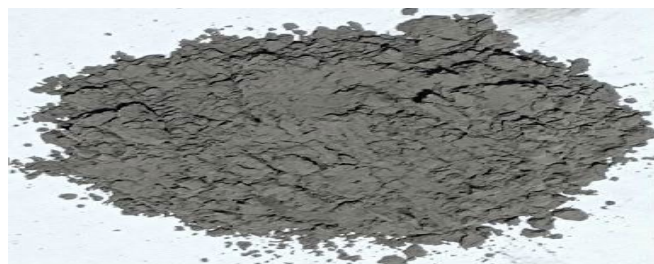


(a) Lead-zinc tailing micropowder

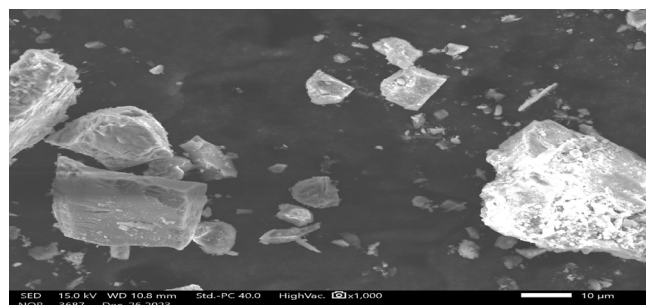


(b) SEM image of lead-zinc tailing micropowder

Figure 2: Steel slag micropowder and its SEM image ($\times 1000$)



(a) teel slag micropowder



(b) SEM image of steel slag micropowder

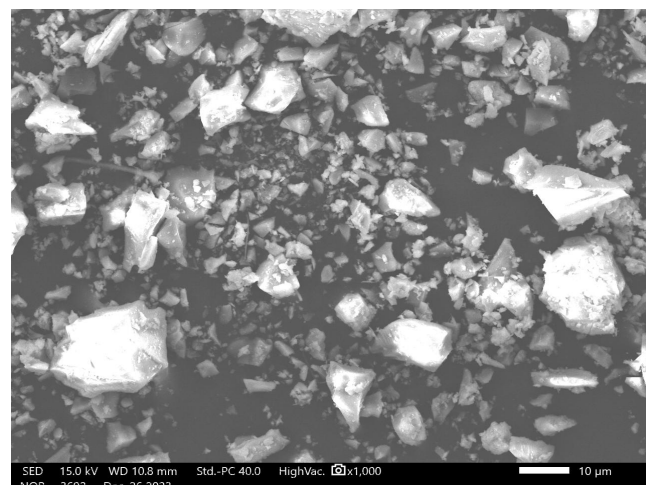
Table 1: Raw material XRF test results

Lead zinc tailings			Slag			Steel slag		
Element	Result		Element	Result		Element	Result	
CaO	41.89	%	CaO	41.843	%	SiO ₂	42.371	%
Fe ₂ O ₃	20.659	%	SiO ₂	32.929	%	Fe ₂ O ₃	24.528	%
SiO ₂	20.468	%	Al ₂ O ₃	14.115	%	CaO	17.062	%
MgO	6.200	%	MgO	7.427	%	Al ₂ O ₃	6.310	%
MnO	3.939	%	SO ₃	1.723	%	MnO	4.083	%
Al ₂ O ₃	3.510	%	TiO ₂	0.591	%	SO ₃	3.922	%
P ₂ O ₅	1.250	%	K ₂ O	0.524	%	K ₂ O	0.983	%
TiO ₂	0.910	%	Fe ₂ O ₃	0.377	%	ZnO	0.445	%
Cr ₂ O ₃	0.430	%	MnO	0.353	%	PbO	0.164	%
SO ₃	0.280	%	SrO	0.071	%	SnO ₂	0.049	%
V ₂ O ₅	0.257	%	ZrO ₂	0.034	%	Cr ₂ O ₃	0.034	%
K ₂ O	0.098	%	Y ₂ O ₃	0.009	%	V ₂ O ₅	0.030	%
SrO	0.036	%	Rb ₂ O	0.003	%	SrO	0.014	%
ZrO ₂	0.036	%				ZrO ₂	0.006	%
ZnO	0.026	%						
NbO	0.012	%						

Figure 3: Slag micropowder and its SEM image ($\times 1000$)



(a) Slag micropowder



(b) SEM image of slag micropowder

As illustrated in Figures 1–3: The lead-zinc tailing micro powder exhibits relatively uniform particle sizes, with near-spherical shapes and large interparticle pores. The steel slag micro powder displays irregular particle sizes and shapes, accompanied by significant interparticle voids. The slag micro powder features irregular particle sizes and shapes but demonstrates tighter particle packing with smaller interparticle pores. As shown in Table 1, the lead-zinc tailings, slag, and steel slag share similar compositional profiles. The lead-zinc tailings primarily consist of CaO, Fe₂O₃, SiO₂, MgO, MnO, and Al₂O₃. The slag is dominated by CaO, SiO₂, Al₂O₃, and MgO, while the steel slag contains SiO₂, Fe₂O₃, CaO, Al₂O₃, and MnO. The variations in component content among

these materials provide the potential for synergistic hydration effects between lead-zinc tailings, slag, and steel slag (Zhang et al. (2023), Liu et al. (2023)).

Experimental Design and Procedure

The study focused on two aspects: (1) the influence of mechanochemical treatment duration on the fineness, 7-day, and 28-day strength activity indices of single-component industrial solid wastes; (2) the effects of mechanochemistry on the fineness and strength activity indices of multi-source solid waste mixtures during graded co-grinding. The experimental design is detailed in Table 2, and the key instruments are listed in Table 3. Specific Surface Area Testing via BET Multi-Point Method.

Table 2: Experimental Design and Key Results

No.	Material	Grinding Time (min)	Specific Surface Area	7d Compressive (MPa)	7d Activity (%)	28d Compressive (MPa)	28d Activity (%)
0	450g cement, 1350g ISO sand, 225g			19		22.87	
1	Steel slag	15	3.2299	5.95	31.32%	10.1	44.17%
2	Steel slag	30	3.9903	6.6	34.74%	9.93	43.44%
3	Steel slag	45	4.8596	6.16	32.42%	10.66	46.62%
4	Steel slag	60	5.4378	7.6	40.00%	9.05	39.58%
5	Slag	15	1.9821	19.05	100.26%	20.82	91.03%
6	Slag	30	2.4287	22.55	118.68%	25.68	112.32%
7	Slag	45	2.626	22.67	119.30%	23.87	104.37%
8	Slag	60	3.1764	23.05	121.32%	26.02	113.78%
9	Tailings	15	1.2248	7.2	37.89%	8.43	36.88%
10	Tailings	30	1.5924	7.52	39.56%	8.52	37.24%
11	Tailings	45	2.9736	5.32	27.98%	10.9	47.67%
12	Tailings	60	4.0531	7.85	41.32%	9.63	42.13%
13	300g steel slag grinding 30min, addition 300g tailings co-grinding another 30 min	60	2.0949	8.37	44.04%	9.85	43.08%
14	300g steel slag grinding, 30min, addition 300g slag co-grinding another 30min	60	2.1325	16.43	86.49%	13.98	61.15%
15	300g tailings grinding, 30 min, addition 300g steel slag co-grinding another 30 min	60	1.848	7.55	39.74%	10.97	47.96%
16	300g tailings grinding, 30 min, addition 300g slag co-grinding another 30 min	60	1.2169	13.6	71.58%	13.48	58.97%
17	300g slag grinding, 30 min, addition 300g tailings co-grinding another 30 min	60	1.3907	14.58	76.75%	17.15	75.00%
18	300g slag grinding 30min, addition 300g steel slag co-grinding another 30min	60	2.1388	13.12	69.04%	20.55	89.87%
19	300g steel slag 15min, additong 300g tailings co-grinding 15min, then addition 300g slag co-grinding another 15min	45	1.9149	12.18	64.12%	13.82	60.42%
20	300g steel slag 15min, additong 300g slag co-grinding 15min, then addition 300g tailings co-grinding another 15min	45	2.2054	14.02	73.77%	17.38	76.02%

21	300g slag 15min, addtiong 300g steel slag co-grinding 15min, then addtion 300g tailings co-grinding another 15min	45	1.9173	10.46	55.05%	18.03	78.86%
22	300g slag 15min, addtiong 300g tailings co-grinding 15min, then addtion 300g steel slag co-grinding another 15min	45	1.3537	10	52.63%	32.93	144.02%
23	300g tailings 15min, addtiong 300g slag co-grinding 15min then addtion 300g steel slag co-grinding another 15min	45	4.5171	8.97	47.19%	19.37	84.71%
24	300g tailings 15min, addtiong 300g steel slag co-grinding 15min, then addtion 300g slag co-grinding another 15min	45	3.5256	10.53	55.44%	18.27	79.88%

The procedure included the following steps: (1) Sample Preparation: Grinding and Sieving: Samples (e.g., mineral powder, catalysts) were ground to a particle size $<20\ \mu\text{m}$ and sieved for uniformity. (2) Drying: Samples were oven-dried to remove moisture and volatile impurities. At least 100 mg of sample was sealed in a sample tube for testing. Degassing: Samples were vacuum-degassed to eliminate adsorbed gases, with temperatures kept below the thermal stability limit. (3) Instrument Calibration and Setup: Calibrated using high-purity nitrogen (N_2). Test mode selected based on pore size range (micropores: 0.5–2 nm). (4) Adsorption Testing: Nitrogen adsorption isotherms were measured at constant low temperature by adjusting relative pressure (p/p_0). Pressure and adsorbed gas volume were recorded using pressure sensors and thermometers. (5) Data Analysis: Nitrogen adsorption-desorption curves were plotted with relative pressure (p/p_0) as the x-axis and adsorption volume as the y-axis. BET equation was applied via linear regression to calculate monolayer adsorption capacity and specific surface area.

Mix Design and Testing Protocol: Control Group (No. 0): 450 g cement, 1350 g ISO standard sand, and 225 g water. Test Groups: 30% cement replacement by ground micro powders. For multi-source solid waste blends, components were mixed at 1:1 or 1:1:1 mass ratios, with standard sand and water identical to the control.

Specimen Preparation and Curing: Mortar mixing and compressive strength testing followed Chinese National Standard GB/T17671. Three 40 mm $\times$ 40 mm $\times$ 160 mm prismatic specimens per group were moulded, cured at $20 \pm 1^\circ\text{C}$ and $>90\%$ relative humidity for 24 h, then demoulded. Demoulded specimens were horizontally submerged in water ($20 \pm 1^\circ\text{C}$, spacing $\geq 5\ \text{mm}$, water level $\geq 5\ \text{mm}$ above specimens). Water was replenished periodically without full replacement.

Compressive strengths of control (R_7 , R_{28}) and test samples (R_{07} , R_{028}) were measured at 7 and 28 days. Strength activity indices (A_7 , A_{28}) were calculated using Equations (1) and (2):

$$A_7 = \frac{R_{07}}{R_7} \times 100 \quad (1)$$

$$A_{28} = \frac{R_{028}}{R_{28}} \times 100 \quad (2)$$

where: A_7 —7-day activity index, %;

R_7 —7-day compressive strength of control sample (MPa);

R_{07} —7-day compressive strength of test sample (MPa).

A_{28} —28-day activity index, %;

R_{28} —28-day compressive strength of control sample (MPa);

R_{028} —28-day compressive strength of test sample (MPa).

Table 3: Key Experimental Equipment

Equipment	Model	Manufacturer
Vertical Planetary Ball Mill	SM-500	Shanghai Lichen Bangxi Instrument Technology Co., Ltd.
Specific Surface Area Analyzer	SBT-127	Wuxi Jianyi Instrument Machinery Co., Ltd.
Cement Mortar Vibration Table	ZT-96	Wuxi Jianding Construction Instrument Factory
Cement Mortar Mixer	JJ-5	Wuxi Dianshi Intelligent Industrial Technology Co., Ltd.
Cement Curing Chamber	SJY-32B	Beijing Yaohua Luye Instrument Co., Ltd.
Electromechanical Compression Tester	YAW-300C	Wuxi Zhongke Building Materials Instrument Co., Ltd.

Analysis Of Experimental Results

The effects of mechanochemistry on lead-zinc tailings, steel slag, slag, and their blends are summarized in Table 2 and Figures 4–7. Key conclusions are as follows:

Figure 4: Specific surface area of tested samples

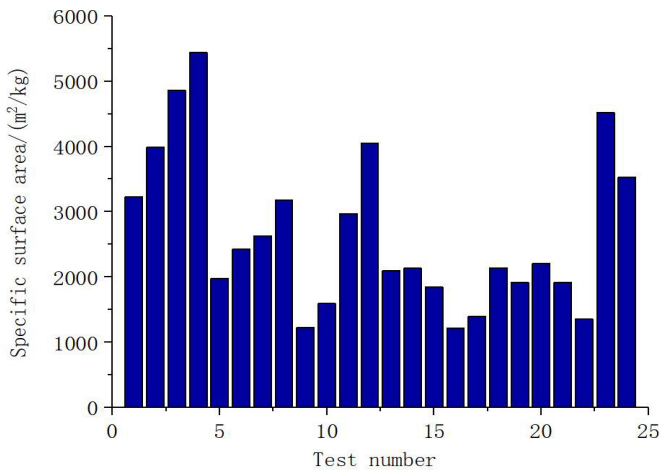
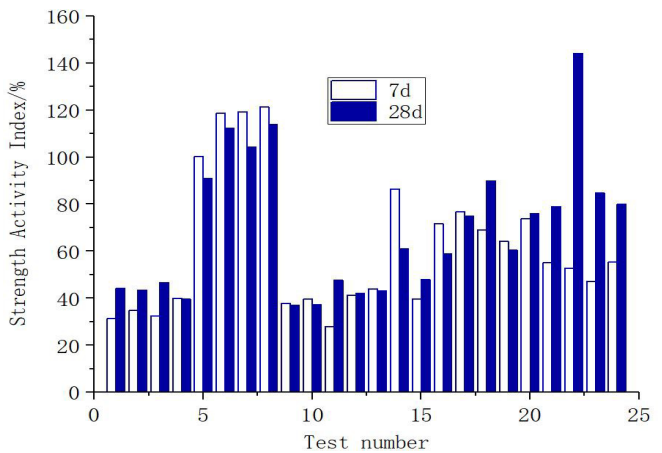


Figure 5: 7d & 28d Strength activity index of tested samples



Relationship Between Grinding Time and Specific Surface Area

The correlation between mechanochemical treatment and the specific surface area of steel slag is illustrated in Figure 6 and Table 4. The specific surface area of steel slag micropowder

increased linearly with grinding time, but the growth rate gradually slowed (23% reduction at 60 min). This may be attributed to rapid particle fragmentation during the initial grinding stage (15→45 min), while further refinement near the particle size limit in later stages (45→60 min) required additional energy input, reducing efficiency. For slag (Figure 6 and Table 5), the growth rate exhibited periodic fluctuations: a 57% decline at 30→45 min, followed by recovery at 45→60 min due to equipment adjustments or optimized particle gradation. Intermittent grinding with parameter adjustments is recommended for industrial applications.

Figure 6: Relationship of grinding time and specific surface area (No.1-No.12)

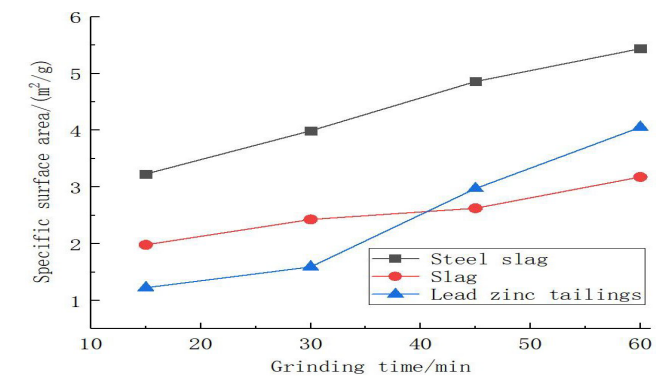


Figure 7: Relationship of grinding time and strength activity index (No.1-No.12)

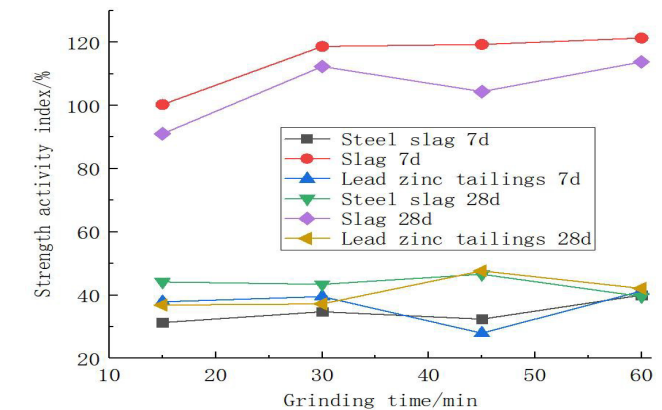


Table 4: Grinding Time vs. Specific Surface Area for Steel Slag

Grinding Time (min)	Specific Surface Area (m²/g)	Growth Rate (m²/g/min)
15	3.23	-
30	3.99	0.051 (15→30min)
45	4.86	0.058 (30→45min)
60	5.44	0.039 (45→60min)

Table 5: Grinding Time vs. Specific Surface Area for Slag

Grinding Time (min)	Specific Surface Area (m ² /g)	Growth Rate (m ² /g/min)
15	1.98	-
30	2.43	0.030 (15→30min)
45	2.63	0.013 (30→45min)
60	3.18	0.037 (45→60min)

Lead-zinc tailings (Figure 6 and Table 6) showed a 268% surge in growth rate at 30→45 min, indicating easier fragmentation of layered structures at medium fineness.

The subsequent decline at 45→60 min likely resulted from the depletion of brittle components and residual ductile particles resisting further refinement

Table 6: Grinding Time vs. Specific Surface Area for Lead-Zinc Tailings

Grinding Time (min)	Specific Surface Area (m ² /g)	Growth Rate (m ² /g/min)
15	1.22	-
30	1.59	0.025 (15→30min)
45	2.97	0.092 (30→45min)
60	4.05	0.072 (45→60min)

(Saedi A., et al., 2023). co-grinding yielded lower specific surface areas than single component grinding due to buffering effects between materials of differing

hardness. The steel slag-slag combination (No. 14) showed higher efficiency, likely due to similar hardness enabling synergistic fragmentation.

Table 7: Specific Surface Area of Two-Stage Co-Ground Mixtures

Material Combination	Total Grinding Time	Specific Surface Area	vs. Single
Steel slag + tailings	60	2.09	38% (vs. steel
Steel slag + slag (No.14)	60	2.13	67% (vs. slag)
Slag + tailings (No.17)	60	1.39	44% (vs. slag)

Three-stage grinding (Figure 4 and Table 8) revealed that grinding sequence critically influenced specific surface area. Pre-grinding tailings (No.23) achieved 4.52 m²/g,

exceeding the 45-min single-material value (2.97 m²/g), likely due to high surface energy particles promoting subsequent slag/steel slag adsorption and fragmentation.

Table 8: Specific Surface Area of Three-Stage Co-Ground Mixtures

Material Combination & Sequence	Total Grinding Time (min)	Specific Surface Area (m ² /g)	vs. Single Material (45 min)
Steel slag→tailings→slag (No.19)	45	1.91	39% (vs. slag)
Slag→tailings→steel slag (No.22)	45	1.35	51% (vs. tailings)
Tailings→slag→steel slag (No.23)	45	4.52	152% (vs. tailings)

Relationship Between Grinding Time and Strength Activity Index

The relationship between grinding time and strength activity index for single materials is shown in Table 9, while that for composite materials is presented in Table 10. The following conclusions can be drawn from Figures 5, 7, and Tables 2 and 9: Steel Slag (Nos. 1-4): The 7-day

activity showed a fluctuating upward trend with increasing grinding time (15 min: 31.32% → 60 min: 40%), but decreased at 45 min (32.42%). The 28-day activity exhibited no clear pattern (15 min: 44.17% → 60 min: 39.58%), potentially due to particle gradation deterioration caused by over-grinding. Notably, the 60-min grinding achieved the highest 7-day activity (40%) but the lowest 28-day activity (39.58%), necessitating

Table 9: Strength Activity Indices of Single Materials

	Grinding	7-day Activity	28-day Activity	Optimal	Optimal	Trend
Material	Time (min)	Range (%)	Range (%)	Grinding Time (7-day)	Grinding Time (28-day)	Analysis
Steel slag	15–60	31.32–40.00	39.58–46.62	60 min	45 min	7-day ↑ with time; 28-day peaks at 45 min
Slag	15–60	100.26–121.32	91.03–113.78	60 min	60 min	Both indices↑ with time
Tailings	15–60	27.98–41.32	36.88–47.67	60 min	45 min	7-day fluctuates;28-day peaks at 45 min

a balance between early-age and long-term strength requirements Li XF et al. (2021). specific surface area. Slag demonstrated sensitivity to grinding time, with specific surface area (1.98 → 3.17 m²/g) positively correlating with activity indices, suggesting extended grinding improves reactivity.

Lead-Zinc Tailings (Nos. 9-12): The 7-day activity fluctuated markedly (15 min: 37.89% → 60 min: 41.32%), plunging to 27.98% at 45 min. The 28-day activity peaked at 45 min (47.67%) but declined to 42.13% at 60 min. This indicates a potential optimal grinding time (45 min) for enhancing later-age

Table 10: Strength Activity Indices of Mixed Materials

Combination Type	7-day Activity (%)	28-day Activity (%)	Key Findings
Steel slag + tailings	39.74–44.04	43.08–47.96	Activity < slag alone but > steel slag alone
Steel slag + slag	69.04–86.49	61.15–89.87	Grinding sequence impacts 28-day performance
Tailings + slag	71.58–76.75	58.97–75.00	High 7-day but lower 28-day vs. slag alone
Three-component blends	47.19–73.77	60.42–144.02	Synergy or gradation optimization enhances 28-day activity

strength in lead-zinc tailings, albeit at the cost of reduced early-age performance (7-day activity drop).

For hybrid materials (Nos. 13–24), s shown in Figures 5, 7 and Tables 2, 10, the activity of steel slag + tailings/slag co-grinding combinations is generally lower than that of pure slag (e.g., 7-day activity of Sample 14: 86.49% vs. slag alone: 121.32%). However, the slag + 238 tailings combination (Sample 22) achieved a 28-day activity of 144.02%, indicating a synergistic effect, likely due to slag filling tailings’ pores and enhancing density. This demonstrates that hybrid grinding activity is significantly influenced by material combinations and grinding sequences, necessitating optimization of ratios and processes. Slag generally exhibits higher 7-day and 28-day strength activity indices compared to steel slag and tailings. For example, at 15 min grinding, 7-day activity of slag is 100.26%, 7-day activity of steel slag is 31.32%, and 7-day activity of tailings is 37.89%. This highlights slag’s superior reactivity and greater contribution to strength enhancement. For hybrid grinding systems, mixtures containing slag typically outperform those with tailings. For instance, 7- day activity of 300g steel slag (30min) + 300g slag(30min) is86.49%, 7-day activity

of 300g steel slag (30min) + 300g tailings (30min) is 44.04%. This suggests slag effectively boosts activity in hybrid systems, likely due to its pozzolanic effect synergizing with the alkaline environment of steel slag/tailings to accelerate hydration.

Grinding sequence critically impacts activity. Grinding slag first, then blending with steel slag (Sample 18: 28-day activity = 89.87%) outperforms the reverse order (Sample 14: 61.15%), attributed to optimized particle gradation and interfacial reaction efficiency. Three-material hybrid systems (e.g., Samples 22, 24), 28-day activities generally exceed single-material systems, demonstrating enhanced reactivity through multi-component complementary effects. However, slag + tailings mixtures (Sample 17: 75.00%) underperform compared to pure slag, likely due to tailings diluting slag’s effective active components.

Relationship Between Specific Surface Area and Strength Activity Index

The relationships between specific surface area and activity index of individual materials are summarized in Tables 11-13.

Table 11: Steel Slag: Specific Surface Area vs. Activity

Specific Surface Area (m ² /g)	7-day Activity (%)	28-dayActivity (%)	Key Pattern
3.23 → 5.44	31.32 →40.00	44.17 →39.58	Early-stage positive and late-stage negative correlation: 7d activity increases with rising specific surface area ($R^2 \approx 0.85$), attributed to finer particles accelerating hydration kinetics 28d activity declines when specific surface area exceeds 4.86 m²/g (46.62%→39.58%), likely due to ultrafine particle agglomeration increasing porosity.

Table 11 shows that prolonged grinding time of steel slag (15→60 min) increases specific surface area from 3.23 to 5.44 m²/g, with 7d activity rising from 31.32% to 40.00% due to finer particles accelerating early hydration reactions¹⁴.

When specific surface area exceeds 4.86 m²/g (grinding time >45 min), 28d activity drops sharply from 46.62% to 39.58%. This is attributed to agglomeration of ultrafine particles via van der Waals forces, forming internal pores and reducing compactness³⁴.

Table 12 indicates that increasing slag's specific surface area from 1.98 to 3.18 m²/g enhances 7d activity by 21% (100.26%→121.32%) and 28d activity by 25% (91.03%→113.78%), aligning with the principle that finer particles improve cementitious activity¹⁵.

The 28d activity decreases to 104.37% at 2.63 m²/g, possibly due to uneven distribution of hydration products and localized stress concentration from excessive fineness⁴⁵.

Table 12: Slag: Specific Surface Area vs. Activity

Specific Surface Area (m ² /g)	7-day Activity (%)	28-dayActivity (%)	Key Pattern
1.98 → 3.18	100.26 →121.32	91.03 →113.78	Strong positive correlation: 7d activity exhibits a linear relationship with specific surface area ($R^2 = 0.98$), with a 1 m²/g increase in fineness corresponding to ~13% activity enhancement. 28d activity generally follows this trend but shows a slight decline at 45 min (104.37%), likely due to hydration product inhomogeneity caused by excessive particle refinement.

Table 13 reveals that lead-zinc tailings exhibit nonlinear fineness-activity dependence. At 2.97 m²/g, 7d activity plummets to 27.98% because fine particles absorb water to form surface films that hinder cement contact³⁴.

28d activity peaks at 47.67% with 2.97 m²/g, as medium fineness balance's reaction rate and gradation while reducing porosity.

Table 13: Tailings: Specific Surface Area vs. Activity

Specific Surface Area (m ² /g)	7-day Activity (%)	28-day Activity (%)	Key Pattern
1.22 →4.05	37.89→ 41.32	36.88→ 47.67	Contradictory relationship: 7d activity sharply decreases to 27.98% at 2.97 m²/g specific surface area, likely due to moisture absorption by fine particles inhibiting early hydration. 28d activity peaks at 47.67% under moderate specific surface area (2.97 m²/g), demonstrating delayed hydration dependence on optimal fineness.

The relationships between specific surface area and activity index of blended materials are summarized in Tables 14 and 15, revealing: (1) High activity in slag-dominated systems with low specific surface area (e.g., Sample 22), where reduced surface area correlates with enhanced reactivity due to optimized particle packing and reduced interfacial defects. (2) Particle gradation

optimization: Slag (1.35 m²/g) fills tailing pores, improving compactness and achieving 28d activity of 144.02% through reduced porosity and enhanced structural continuity. (3) Chemical activation mechanism: Reaction between CaO in slag and SiO₂ in tailings generates C-S-H gel, strengthening microstructure and reducing dependence on high specific surface area.

Table 14: Two-Stage Mixtures: Surface Area vs. Activity

Combination	Specific Surface Area(m ² /g)	7-day Activity (%)	28-day Activity (%)	Key Insight
Steel slag +slag (No.14)	2.13	86.49	61.15	Low Specific Surface Area With High Reactivity: The specific surface area is only 67% of slag ground for 60 minutes, yet the 7d activity reaches 86.49%, indicating that the reactivity of slag-dominated composite systems does not solely depend on fineness
Slag + tailings (No.22)	1.35	52.63	144.02	Exceptional 28d Activity: With a specific surface area of just 1.35 m ² /g, the 28d activity attains 144.02%, attributed to slag filling tailing pores to form a dense microstructure, reducing reliance on high surface area

(4) Grinding sequence effects (e.g., Sample 23): Prioritized grinding of tailings to 4.52 m²/g creates high-surface-energy particles, but limited activity improvement (84.71%) due to inherently weak cementitious properties of tailings. (5) Inhibitory effects in slag-steel slag combinations (e.g., Sample 14): Hardness mismatch (steel slag: Mohs 6-7 vs. slag: 5-6) causes buffering during co-grinding, lowering specific surface area (2.13 m²/g). Concurrently, free CaO in steel slag suppresses slag hydration, resulting in 28d activity of only 61.15%.

Analysis And Discussion

Due to significant differences in particle morphology, size, and spacing among steel slag, slag, and lead-zinc tailings micro powders, the mixed system exhibits a denser microstructure, more uniform particle size distribution, and tighter interparticle packing (Fig.8)

single-component micropowders. This enhanced structural integration promotes synergistic effects during hydration processes.

Figure 8: SEM Image Of Steel Slag-Slag & Lead-Zinc Tailings Micro Powder Mixture (×1000)

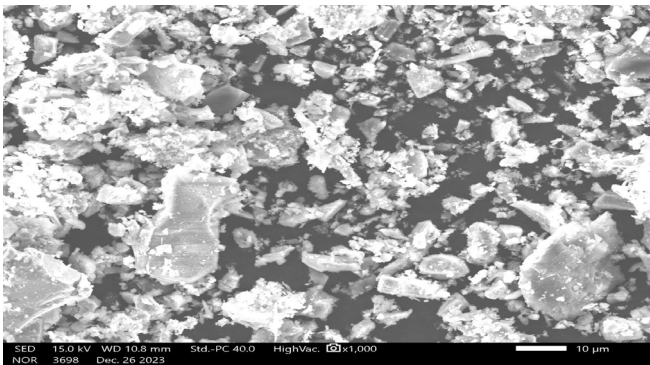


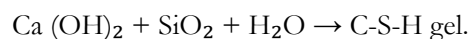
Table 15: Three-Stage Mixtures: Surface Area vs. Activit

Combination	Specific Surface Area (m ² /g)	7-day Activity (%)	28-day Activity (%)	Key Insight
Tailings→slag→steel slag (No.23)	4.52	47.19	84.71	High Specific Surface Area with Low Reactivity: A specific surface area of 4.52 m ² /g (higher than the 4.05 m ² /g of single tailings ground for 60 minutes) correlates with lower activity compared to slag-based systems, demonstrating that elevated surface area in tailings contributes minimally to reactivity

The multi-source solid waste ultrafine powder admixture and cement jointly form a quaternary system (steel slag-slag-lead-zinc tailings-cement). The chemical composition and hydration mechanisms of each component are outlined below:

The composition of steel slag is predominantly SiO_2 , Fe_2O_3 , CaO , and Al_2O_3 , with trace MgO and MnO . Mineral Phases: Dicalcium silicate (C_2S), tricalcium silicate (C_3S), RO phase (iron oxides), and minor free CaO (f- CaO). Hydration: $\text{C}_2\text{S}/\text{C}_3\text{S}$: Slow hydration generates C-S-H gel and $\text{Ca}(\text{OH})_2$ but with lower reactivity than cement clinker. RO phase: Inert filler; fine grinding enhances microcrystalline nucleation to accelerate hydration. f- CaO : Causes volumetric expansion; requires strict content control Deniz A et al. (2022).

The composition of slag is high-calcium aluminosilicate glass ($\text{CaO-SiO}_2\text{-Al}_2\text{O}_3$) with minor MgO and sulfides. Hydration: Glassy structure depolymerizes under alkaline conditions ($\text{pH} > 12$), releasing reactive SiO_2 and Al_2O_3 for secondary hydration:



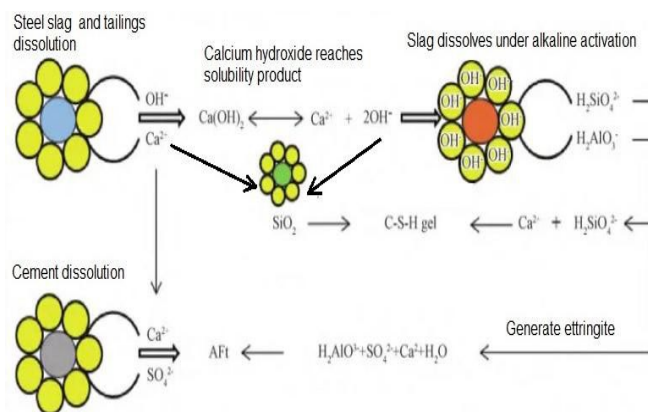
Sulfides (e.g., CaS): Generate ettringite (Aft), improving early strength.

The composition of lead-zinc tailings mainly is CaO , Fe_2O_3 , SiO_2 , and Al_2O_3 . Hydration: $\text{C}_2\text{S}/\text{C}_3\text{S}$: Slow hydration produces C-S-H gel and $\text{Ca}(\text{OH})_2$, with lower activity than cement clinker. Inert components (e.g., quartz): Act as micro-aggregates to fill pores and enhance compactness.

Cement clinker dominant reaction: rapid hydration of $\text{C}_3\text{S}/\text{C}_2\text{S}$ generates C-S-H gel and $\text{Ca}(\text{OH})_2$, providing early strength.

The quaternary system exhibits synergistic effects in three dimensions (Fig.9):

Figure 9: Synergistic Hydration Process of Steel Slag-Slag-Lead Zinc Tailings-Cement System (Modified from Zheng et.al. (2022))



Chemical Synergy

Alkaline Activation: $\text{Ca}(\text{OH})_2$ from cement hydration creates an alkaline environment, promoting depolymerization of slag and steel slag glass phases. Secondary Hydration: Active $\text{SiO}_2/\text{Al}_2\text{O}_3$ from slag reacts with $\text{Ca}(\text{OH})_2$ to form C-S-H/AFm phases, reducing porosity. Long-Term Strength: C_2S in steel slag gradually hydrates to supplement C-S-H gel, enhancing later strength. Heavy Metal Stabilization: $\text{Pb}^{2+}/\text{Zn}^{2+}$ from tailings integrate into C-S-H interlayers via ion exchange, forming stable complexes (e.g., Ca-Pb-Si-O).

Physical Synergy

Micro-Aggregate Filling: Inert particles from tailings and steel slag reduce permeability by filling pores. Nucleation Effect: RO phase (steel slag) and unreacted microcrystalline particles (slag) act as nucleation sites for C-S-H gel, accelerating hydration.

Temporal-Spatial Synergy

Early Stage: Cement clinker dominates hydration for initial strength, while slag mitigates heavy metal inhibition. Later Stage: Secondary hydration of steel slag and slag continuously generates C-S-H, compensating for strength stagnation during cement hydration slowdown.

CONCLUSIONS

Through the experimental testing and analysis above, the following conclusions can be drawn:

Single-Material Performance. For steel slag, slag, and lead-zinc tailings, the specific surface area generally increases with extended grinding duration, indicating that finer grinding enhances material reactivity. 7-Day Compressive Strength: 23.05 MPa (grinding for 60 min) with activity of 121.32%. 28-Day Compressive Strength: 26.02 MPa with activity of 113.78%. Slag exhibits superior early and long-term strength development due to its chemical composition and hydration-friendly mineral structure. Steel slag and tailings show lower activity (~30–40% for 7- and 28-day tests). Steel slag activity reaches 40.00% at 60-min grinding, suggesting prolonged grinding improves reactivity.

Mixed-Material Performance. Combination Effects: Slag + Steel Slag (300g each, 30-min grinding), 28-day compressive strength: 20.55 MPa (activity: 89.87%). Tailings + Steel Slag (300g each, 30-min grinding), 28-day compressive strength: 10.97 MPa (activity: 47.96%). Mixed slag-steel slag systems demonstrate synergistic advantages. Multi-Stage Mixing: Slag (15 min) + Tailings (15 min) + Steel Slag (15 min), 28-day compressive strength: 32.93 MPa (activity: 144.02%). Enhanced late-stage performance arises from synergistic interactions during multi-stage mixing.

Recommendations for optimization: (1) Grinding Parameters: Identify optimal grinding duration, speed, and media to balance specific surface area with strength and activity. Systematic Mixing Studies: Explore diverse mixing ratios and sequences to maximize material synergy and overall performance.

DECLARATIONS

Data Availability

All data generated or analysed during this study are included in this published article.

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Author Contributions

Conceptualization, Liu Jifeng and Lu Jian.; methodology, Lu Jian and Lin Xin; software, Zhong Hai and Qiu Chunlong; validation, Zhang Huizhi; formal analysis, Liu Jifeng and Zhong Hai; investigation, Liu Jifeng; resources, Lu Jian; data curation Lin Xin; writing—original draft preparation, Liu Jifeng; writing—review and editing, Zhong Hai and Lu Jian; supervision, Liu Jifeng; project administration, Zhang Huizhi, Liu Jifeng and Zhong Hai; All authors have read and agreed to the published version of the manuscript.

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Conflicts Of Interest

The authors declare no conflict of interest.

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