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Review

Tailings as low-carbon supplementary cementitious materials: A critical review

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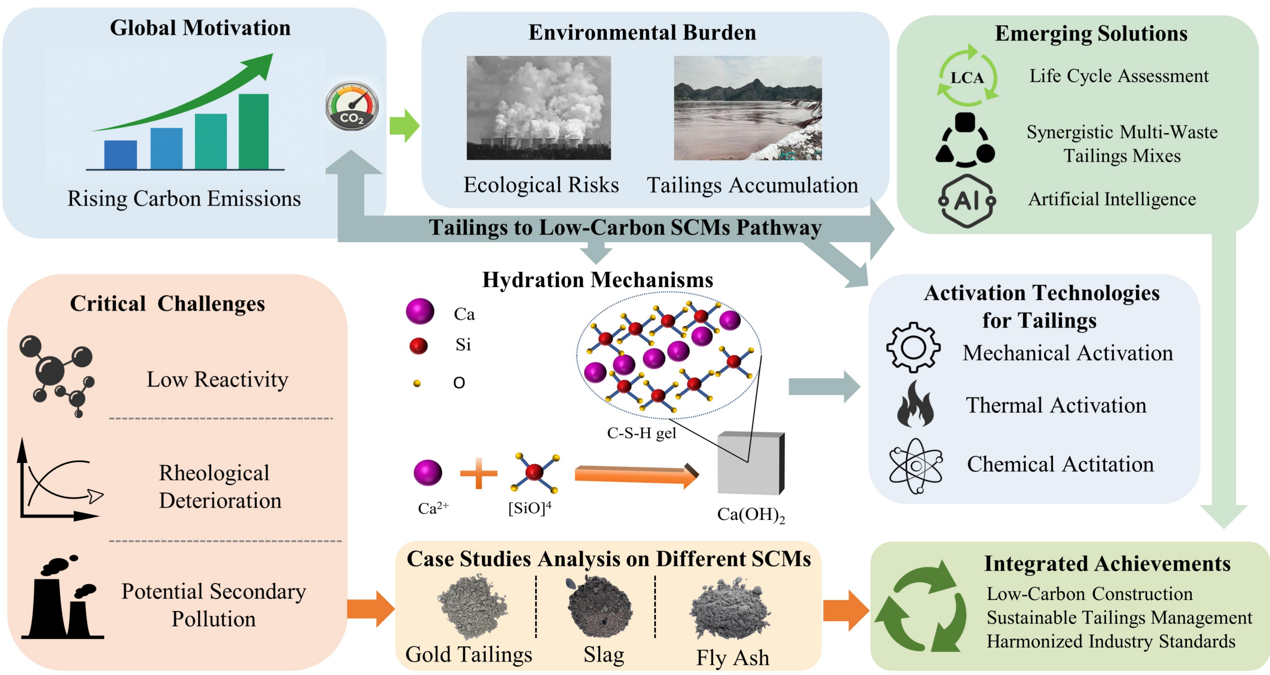
Graphical abstract



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Abstract: Global decarbonization targets are accelerating the low-carbon transition of the construction industry. Meanwhile, the massive accumulation of tailings worldwide poses significant environmental risks. Driven by the need to meet global decarbonization targets while mitigating the environmental burden associated with tailings stockpiles, the use of tailings as supplementary cementitious materials (SCMs) to partially replace ordinary Portland cement (OPC) has received considerable attention. Nevertheless, widespread application remains constrained by several critical challenges, including inherently low reactivity, substantial deterioration of rheological properties, the absence of unified standards, and potential secondary pollution. Furthermore, existing research addressing these issues remains fragmented. To overcome these barriers and provide a comprehensive understanding, this review establishes a foundational framework examining the physicochemical properties, hydration mechanisms, fresh-state performance, and advanced activation technologies of tailings-based SCMs. Building on this foundation, the review further integrates utilization strategies customized for distinct tailings types, life cycle assessment (LCA), and artificial intelligence (AI)-assisted optimization to support sustainable, large-scale implementation. This integrated approach aims to highlight potential pathways from laboratory research to industrial application, providing insights and perspectives for the low-carbon transition of the construction sector, the sustainable management of solid waste, and the development of unified industry standards.

Keywords: tailings, supplementary cementitious materials, activation mechanism, carbon reduction

1. Introduction

The global cement industry remains one of the largest anthropogenic sources of carbon emissions, accounting for approximately 7-8% of global CO_2 emissions. On average, the production of one ton of OPC emits approximately 0.8–1.0 tons of CO_2. As illustrated in **Fig. 1**, global cement-related CO_2 emissions increased markedly from 1995 to approximately 2021, before showing a modest decline during 2022–2024. Despite this recent decrease, the cement sector remains a major and persistent contributor to anthropogenic CO_2 emissions. The long-term increase has been driven largely by major markets such as China, the world's largest cement producer, whose output more than tripled between 2000 and 2023, reaching approximately 2 billion tons [1]. Without effective emission-reduction measures, carbon emissions from the cement industry may continue to increase substantially by 2050, which could significantly hinder the achievement of global net-zero emission targets. SCMs can effectively reduce cement consumption and associated CO_2 emissions by partially replacing cement clinker. In addition, they can improve the long-term durability, mechanical performance, and microstructural characteristics of concrete. This strategy is widely recognized as one of the most mature and effective strategies for producing low-carbon construction materials [2]. Although traditional SCMs such as fly ash, ground granulated blast-furnace slag, and silica fume are widely used in industry, the availability of high-quality feedstocks is becoming increasingly scarce due to energy transition, industrial restructuring, and geographical constraints. Consequently, developing novel sustainable SCMs has become a global priority.

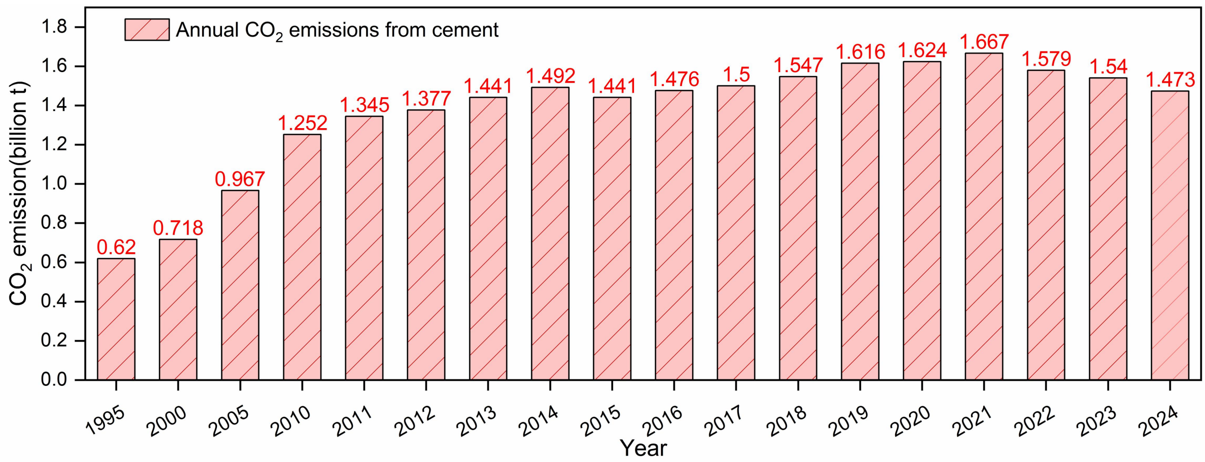


Fig. 1. CO_2 emissions of annual global cement [3].

Meanwhile, the global mining industry generates billions of tons of solid waste annually. The massive accumulation of these tailings occupies extensive land resources and poses severe ecological and geotechnical risks. Against this backdrop, the use of tailings as SCMs has emerged as a promising dual-benefit solution. Consequently, current research has increasingly focused on three key dimensions: the macro-scale assessment of emerging tailings resources, underlying mechanisms at the microstructural level, and advanced activation strategies. Regarding resource potential and sustainability, Snellings et al. [2] and Juenger et al. [4] have identified mining waste as a critical emerging resource for low-carbon concrete, emphasizing the need for rigorous, standardized evaluations. At the microstructural scale, Chandran et al. [5] established core screening indicators, including active oxide and amorphous phase contents, while Guo et al. [6] analyzed their physicochemical properties and toxicological safety. Building on these mechanisms, advanced activation strategies have been widely explored to overcome the inherently low reactivity of stable mineral phases such as quartz. Gou et al. [7] emphasized that targeted pretreatments, such as mechanical and thermal activation, are necessary to disrupt crystalline structures and stimulate latent pozzolanic activity, thereby providing a technical pathway for the high-value conversion of these wastes.

However, the large-scale industrial deployment of tailings-based SCMs currently faces several critical constraints. First, with respect to material properties and workability, many raw tailings exhibit low intrinsic pozzolanic reactivity because of the predominance of stable crystalline phases and the limited content of amorphous constituents. Furthermore, fine tailings often exhibit highly irregular particle morphologies and high specific surface areas that significantly impair the rheological properties of fresh concrete. Second, in terms of long-term durability and environmental safety, although cementitious encapsulation can generally immobilize heavy metals, long-term environmental weathering can degrade the matrix and reactivate heavy-metal leaching. Additionally, the slow oxidation of residual sulfides in polymetallic tailings may induce delayed internal sulfate attack (ISA), thereby compromising long-term structural integrity. Compounding these inherent material and environmental challenges, current research frameworks reveal significant limitations in fully understanding and mitigating these risks. Previous studies have mainly focused on early-age mechanical properties, whereas microstructural evolution and long-term durability under complex service environments remain insufficiently understood. Moreover, current LCA studies often fail to differentiate between preliminary screening and full sustainability assessments. Simplified cradle-to-gate boundaries are appropriate for early-stage technical ranking but are insufficient for final industrial validation. Therefore, relying on them as the sole evaluation basis leads to a systematic underestimation of long-term ecological risks. Consequently, overcoming these multiple barriers requires moving beyond isolated case studies to systematically evaluate current mitigation technologies and redefine long-term sustainability frameworks.

Recently, several valuable reviews have summarized the use of specific tailings. For instance, recent studies have summarized the macroscopic mechanical performance of iron ore tailings and evaluated basic activation strategies [8]. Although microstructural development has been explored in several studies, existing reviews predominantly focus on individual types of tailings [9]. As a result, the literature on this topic remains fragmented. Furthermore, most current studies rely on single activation methods instead of exploring more effective multi-coupled activation strategies. Furthermore, cross-disciplinary integration is limited, particularly regarding the synergistic effects among diverse tailings and the adoption of advanced analytical frameworks, such as comprehensive LCA and AI-assisted approaches. To systematically address these interconnected research gaps, this review develops an integrated framework covering tailings characterization, fundamental performance, hydration behavior and fresh-state properties, activation technologies, tailings-type-specific utilization pathways, life-cycle and environmental assessment, and AI-assisted future development. Particular attention is devoted to the underlying effects of tailings on hydration kinetics, microstructural densification, and long-term durability. In addition, dedicated assessments are provided for iron ore tailings, gold tailings, and copper tailings to elucidate their respective characteristics and application potentials. Furthermore, emerging research directions, particularly AI-driven dynamic mixture-design optimization and multi-solid-waste synergistic utilization, are highlighted. Unlike previous reviews that focus on isolated materials or methods, this paper attempts to integrate multi-solid-waste synergistic utilization, dynamic AI optimization, and full-life-cycle sustainability into a cohesive framework. Ultimately, this review aims to provide a robust theoretical basis and practical guidance for the safe, sustainable, and large-scale implementation of tailings-based low-carbon concrete.

2. Properties and mechanisms of tailings as SCMs

2.1. Physicochemical properties

Tailings are fine particulate solid residues generated in massive quantities during the beneficiation of metallic and non-metallic ores. Following the extraction of valuable minerals through crushing, grinding, and physicochemical separation, these residues are typically discharged into storage facilities. Tailings constitute one of the largest global industrial solid-waste streams, with major environmental consequences. Approximately 13–25 billion tons of tailings are generated worldwide each year, resulting in a cumulative stockpile exceeding 280 billion tons (equivalent to a volume of about 217 km^3) and an additional annual storage volume of around 12.3 km^3 [10]. Within this context, some assessments report that the annual generation of fine-grained tailings alone reaches approximately 14 billion tons worldwide [11]. As a dominant global mineral producer, China maintains a cumulative tailings stockpile exceeding 20 billion tons, comprising predominantly iron, copper, and gold residues [12]. Within this inventory, the domestic gold tailings stockpile in China has surpassed 200 million tons, increasing at an annual rate of approximately 24.5 million tons [13].

The long-term, large-scale impoundment of these materials occupies extensive land resources and creates severe geotechnical and environmental liabilities. Without rigorous engineering controls, these facilities are susceptible to structural failures such as static liquefaction, while the geochemical instability of sulfide minerals can induce persistent acid mine drainage and the leaching of heavy metals [14]. Moreover, complex hydrometallurgical processing can leave residual flotation reagents and hazardous constituents within the tailings matrix, including cyanide, cadmium, chromium, lead, arsenic, and pyritic sulfur [15–18]. During such prolonged storage, these toxic constituents are susceptible to leaching through precipitation and surface runoff, generating acidic wastewater that can cause severe environmental damage. Consequently, the fine particle size of many tailings, together with toxicity and leaching concerns, creates a dual barrier to their use in building materials and indirectly aggravates storage-pressure problems when valorization pathways remain limited [19]. The persistent toxicity risk posed by these hazardous components, together with the immense volume of unrecovered strategic minerals trapped within the waste, necessitates rigorous stabilization and detoxification strategies before final disposal or secondary resource valorization [20].

Despite these environmental challenges and limitations to utilization, tailings exhibit inherent physicochemical compatibility with conventional SCM systems, which serves as a key prerequisite for their application as SCMs. Physically, tailings exhibit a wide particle-size distribution (D_{50}: 10–100 μm), a specific surface area typically below 500 m^2/kg, a true density of 2.6–4.3 g/cm^3, and relatively high water absorption (7%–9%) [6]. To further illustrate these physical variations, the detailed particle size distributions and specific gravities (ρ_s) of various typical tailing samples are summarized in **Table 1**.

Table 1. Specific gravity and particle size distribution of various tailing sample [21].

Samples	ρ_s	PSD Measured Curve, μm					
		d_{10}(1)	d_{30}(2)	d_{50}(3)	d_{60}(4)	d_{70}(5)	d_{90}(6)
Copper tailing: S1	3.02	1.76	6.41	14.42	20.43	28.71	64.62
Copper tailing: S2	2.64	2.25	9.34	36.27	56.83	81.42	172.7
Copper-Nickel tailing: S3	2.94	2.62	10.56	27.94	42.53	62.52	132.5
Polymetallic tailing: S4	3.19	2.75	12.86	33.71	53.15	82.34	203.6
Copper tailing: S5	2.87	2.75	13.15	39.58	68.51	116.4	251
Copper tailing: S6	2.75	2.95	11.78	28.97	43.56	65.03	151.5
Copper tailing: S7	2.98	3.31	23.54	78.86	119.8	179.2	393.4
Copper-Gold tailing: S8	2.95	4.44	11.1	21.88	31.21	45.9	118.8
Copper-Gold tailing: S9	2.94	7.24	40.4	76.42	99.45	130.4	268.9
Copper tailing: S10	2.96	9.31	46.57	82.46	105.5	137.3	284.1
Iron tailing: S11	2.84	10.22	42.7	79.81	104.4	137.8	296.3
Copper tailing: S12	2.94	13.62	50.82	106.9	137.8	179.2	345.6

Note: d_n denotes the equivalent particle diameter such that n% of the total particle mass is finer than this value (on a cumulative mass passing basis). Specifically, d_{50} corresponds to the median particle size, while parameters such as d_{10} and d_{90} define the finer and coarser endpoints, collectively reflecting the overall particle size distribution and span. Unit: μm.

Advanced micro-CT characterizations reveal a pronounced particle-size-dependent morphological differentiation: coarse tailings fractions (0.15–0.3 mm) exhibit highly irregular and angular shapes, whereas finer fractions (0.075–0.15 mm) possess complex internal pore networks [22]. This inherent porosity helps explain their high water-retention capacity. Although the specific surface area of many raw tailings is lower than that of finely ground SCMs, their angular morphology and complex internal pore networks still significantly increase water demand compared with spherical fly ash or well-graded aggregates. Chemically, the total content of active oxides (SiO_2+Al_2O_3+Fe_2O_3) generally ranges from 50% to 70%. While this provides only a potential chemical basis for pozzolanic reactivity, the actual activity is governed by multiple factors, including amorphous phase content, mineral lattice stability, particle fineness, activation state, and the presence of deleterious components. Therefore, chemical composition should be evaluated in conjunction with mineralogical characteristics and environmental risk indicators to comprehensively assess SCM suitability. For example, sulfide-rich copper tailings are enriched in silica, iron oxides, and potentially leachable heavy metals (e.g., arsenic), whereas laterite-derived tailings contain elevated levels of alumina and calcium-bearing phases. Iron tailings often contain residual CaO, while copper and gold tailings are predominantly siliceous. Furthermore, the amorphous phase content, which is the key prerequisite for pozzolanic reactivity, is closely related to the lattice stability of the dominant minerals. While inert quartz dominates many tailings, others contain moderately reactive phases such as feldspars and kaolinite. Therefore, detailed mineralogical characterization is essential before formulating tailored activation protocols [23].

2.2. Reaction mechanisms

Fundamentally, the feasibility of utilizing typical aluminosilicate tailings as SCMs is supported by their chemical similarity with traditional cementitious materials. Most tailings primarily contain major oxides such as SiO_2, Al_2O_3, and Fe_2O_3. When appropriately pretreated through mechanical, thermal, or chemical activation, tailings may exhibit pozzolanic activity, latent hydraulic behavior, or primarily act as physical fillers, depending on their specific mineralogy, amorphous fraction, and chemical environment. Within the cementitious system, these materials function through a combination of mechanisms. First, they refine the pore structure through the micro-filling effect of reactive particles. Second, where chemically active, they form secondary calcium silicate hydrate (C-S-H) gel through reaction with $Ca(OH)_2$. This synergistic action leads to microstructural densification and improvements in long-term durability [24].

SCMs can contribute to cementitious systems through pozzolanic reactions, latent hydraulic reactions, or predominantly through physical filler effects. Therefore, tailings should be classified according to their dominant contribution mechanism, as their role in cementitious systems may range from chemically reactive behavior to predominantly inert filler effects. For reactive tailings, their contribution to performance mainly arises from secondary pozzolanic reactions to form additional C-S-H gel, whereas filler-type tailings mainly improve packing density, with both mechanisms contributing to matrix densification and pore refinement [25]. **Fig. 2** illustrates this secondary hydration mechanism.

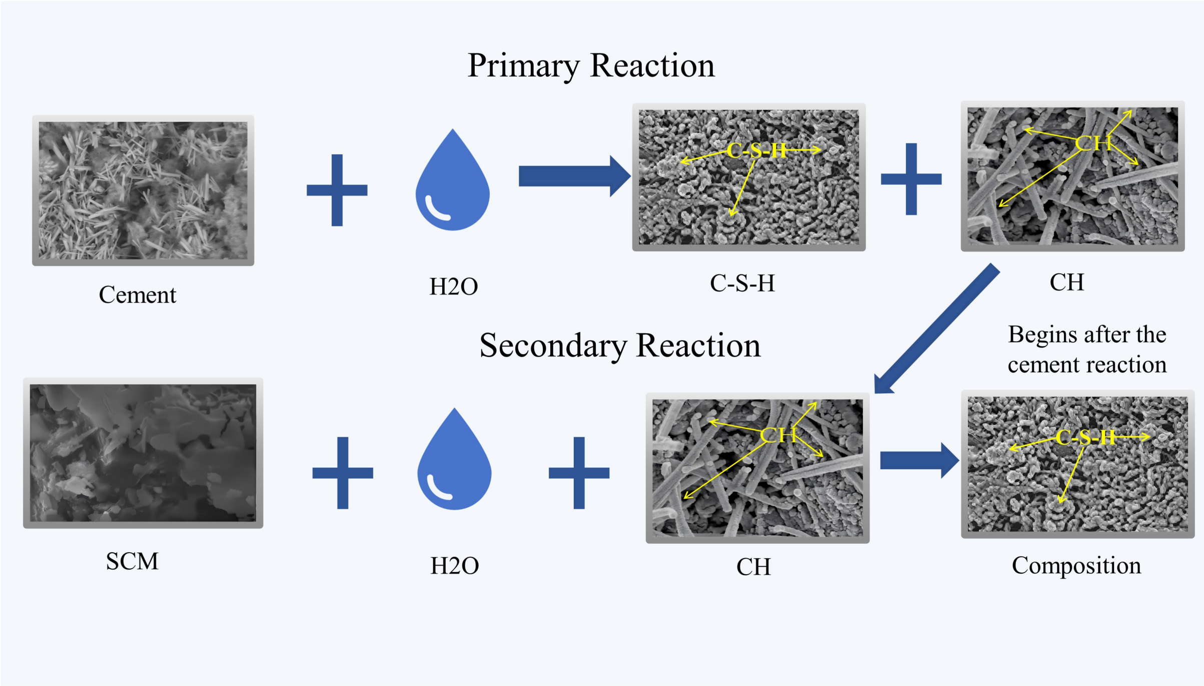


Fig. 2. Schematic diagram of primary cement hydration and secondary pozzolanic reaction of supplementary cementitious materials [26–28].

SCMs fall into three categories: pozzolanic, latent hydraulic, and filler-type materials (**Fig. 3**). Their reactivity is primarily governed by three parameters: total active oxide content (SiO_2+Al_2O_3+Fe_2O_3), amorphous phase fraction, and particle fineness are standard preliminary metrics for reactivity screening [29].

However, the actual reactivity of SCMs depends on the interplay between intrinsic material attributes and external reaction conditions. Intrinsically, the mineralogical assemblage and lattice stability of primary phases set the fundamental limit of pozzolanic potential. For example, chemically inert quartz exhibits far lower reactivity than moderately reactive feldspars or clay minerals. Beyond the bulk mass fraction of amorphous phases, their structural order, silicate polymerization degree, and defect density exert critical control over mineral dissolution kinetics in alkaline pore solutions. Extrinsically, factors such as pore solution alkalinity, calcium ion availability, curing temperature, and admixture adsorption behavior all significantly modulate the hydration kinetics and final reaction extent of SCM particles. The coupled action of these interrelated variables ultimately defines the functional performance of SCMs in cementitious matrices.

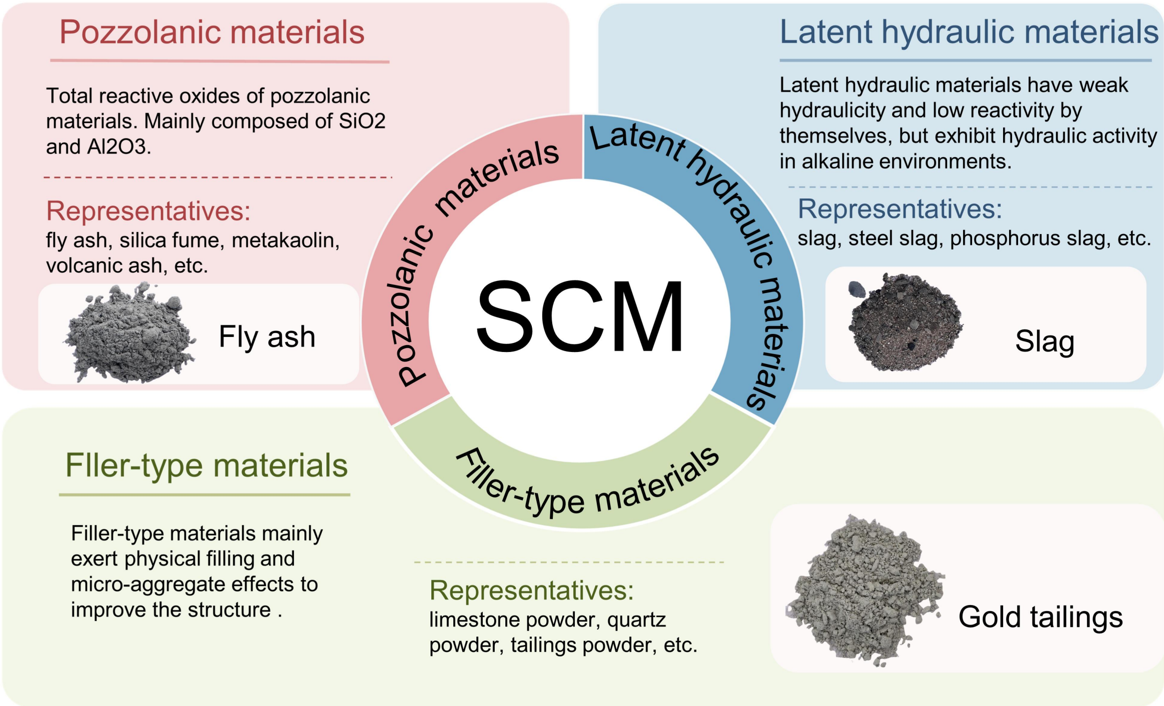


Fig. 3. Classification and functional mechanisms of SCMs.

Guided by these theoretical mechanisms and evaluation parameters, extensive investigations have demonstrated the feasibility of using tailings as SCMs (**Table 2**). To illustrate this, Simonsen et al. [30] characterized 13 different tailings samples. They mapped their chemical compositions in a CaO-SiO_2-(Al_2O_3+Fe_2O_3) ternary phase diagram (**Fig. 4**). The experimental results identified five samples with favorable combinations of oxide chemistry, mineralogical state, and fineness. These samples also passed strict environmental and leaching assessments, thereby enabling their direct use as SCMs

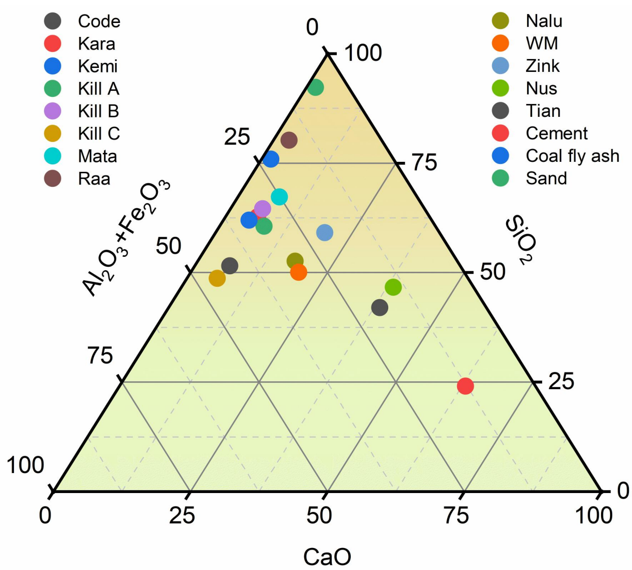


Fig. 4. Chemical composition of mine tailings and reference samples (cement, coal fly ash, and sand) plotted in a CaO-SiO_2-Al_2O_3 + Fe_2O_3 ternary phase diagram [30].

The overall technical pathway for converting tailings, a bulk mining solid-waste stream, into green supplementary cementitious materials is illustrated in **Fig. 5**. This pathway follows a sequential three-step approach. First, it relies on the chemical homology and physical compatibility between tailings and traditional SCMs. Second, it activates their inherent pozzolanic activity and latent hydraulicity through appropriate pretreatment technologies. Ultimately, this synergistic approach achieves the coordinated decarbonization of the cement industry alongside solid-waste valorization.

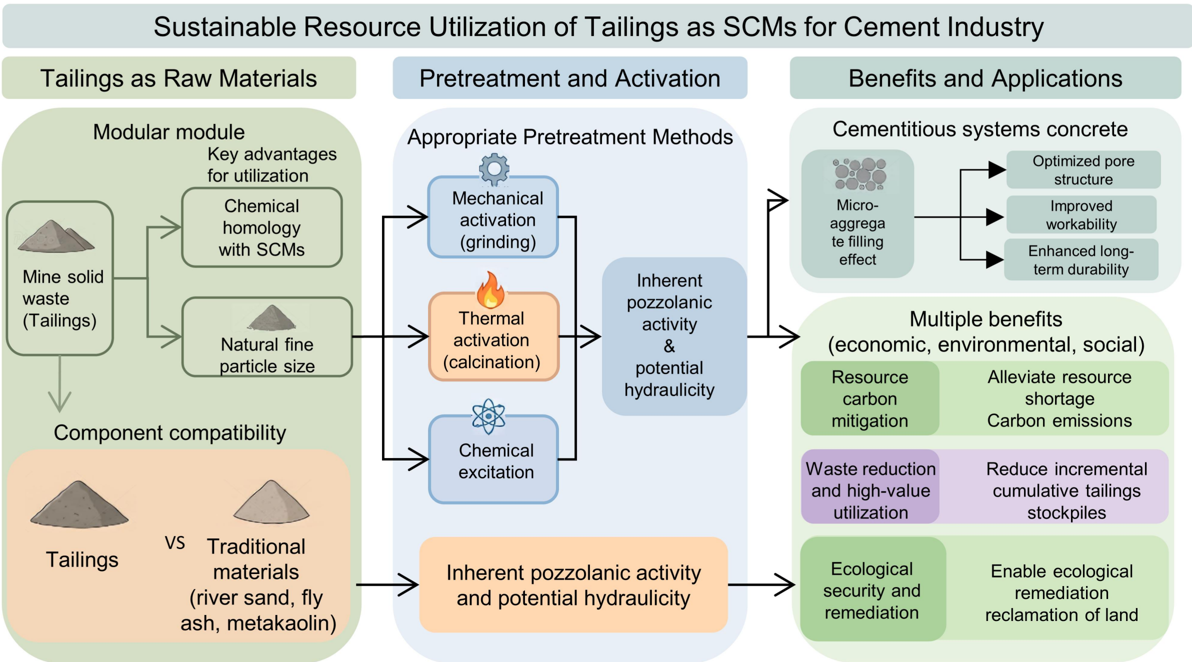


Fig. 5. Sustainable resource utilization of tailings as SCMs for the cement industry.

Ultimately, although tailings from diverse sources exhibit significant heterogeneity, some tailings exhibit selected physicochemical features that overlap with those of traditional SCMs. However, their suitability must first be confirmed through comprehensive mineralogical, reactivity, workability, durability, and environmental assessments. Once validated, appropriate pretreatment methods include mechanical, thermal, and chemical techniques. These methods effectively stimulate latent pozzolanic reactivity and enhance the micro-filling effect. This transition facilitates the shift in mining solid-waste management from conventional end-of-pipe disposal to high-value valorization, providing a technically viable and industrially scalable pathway for the decarbonization of the cement industry.

Table 2. Studies on tailings used as SCMs.

Researchers	Tailings types	Main Research Contents
Yague et al. [31]	Coal tailings	Validation of coal tailings as effective SCMs through the thermal conversion of kaolinite into metakaolin.
Zeng et al. [32]	Copper tailings	Systematic investigation of hydration kinetics and microstructural evolution, benchmarking copper tailings against conventional SCMs.
Kara et al. [33]	Copper tailings	LCA demonstrating the environmental benefits of recycled copper tailings as sustainable SCMs.
Arachchilage et al. [34]	Mine tailings	Development of a Transformer-Based Machine Learning Model for Optimizing the Design of Cement-Based Mixtures Containing Tailings as SCMs.
Yi et al. [35]	General tailings	Systematic review of activation mechanisms for improving the reactivity of low-grade tailings toward broader SCM applications.
Fante et al. [36]	Zinc mine tailings	Evaluation of solidification treatment of zinc metallurgical tailings and its environmental, microstructural, and mechanical properties in cement-based materials.
Vigneshwari et al. [37]	Iron ore tailings	Enhancement of pozzolanic reactivity through mechanical activation, enabling the utilization of iron ore tailings as viable SCMs.
Hu et al. [38]	Iron ore tailings	Orthogonal experimental optimization and hydration mechanism analysis of multi-solid-waste synergistic SCM systems.

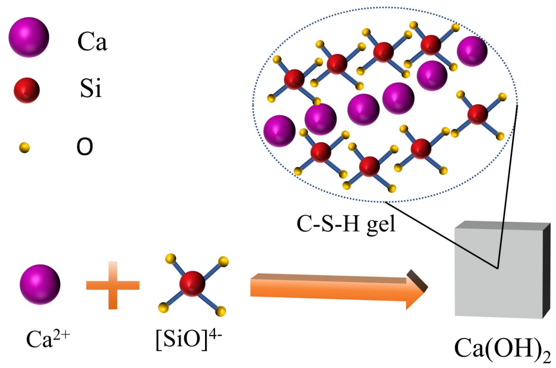
3. Hydration mechanism, fresh properties, and mechanical performance of tailings as SCMs

The integration of tailings into cementitious systems induces coupled physical interactions and chemical reactions that collectively govern the macroscopic performance of the system. Before examining the microstructural evolution, it should be noted that the efficacy of tailings as supplementary cementitious materials depends not only on their chemical reactivity but also on their physical morphology. The following sections present a systematic evaluation of how these intrinsic properties govern both the early-age hydration kinetics and the rheological behavior in the fresh state. Furthermore, they explore how these early-stage microstructural evolutions ultimately control hardened-state mechanical performance, thereby establishing the mechanistic basis for engineering applications.

3.1. Hydration mechanism

In cementitious systems, pozzolanic tailings mainly contribute through dissolution and secondary pozzolanic reactions rather than through independent hydration comparable to OPC clinker. Tailings particles often contain reactive aluminosilicate phases that can dissolve in the highly alkaline pore solution. These activated particles then undergo secondary chemical reactions with $Ca(OH)_2$, a primary by-product of cement hydration, generating secondary C-S-H and C-(A)-S-H gels. This chemical evolution can be described by the following reaction equations:

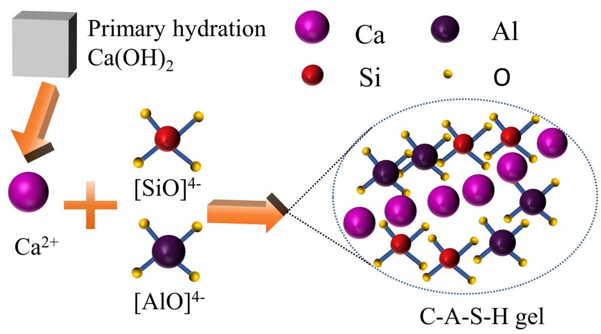
Primary hydration reaction of alite in OPC (**Fig. 6**):



$$3CaO \cdot SiO_2 + 6H_2O \rightarrow C-S-H + 3Ca(OH)_2 \quad (1)$$

Fig. 6. Primary hydration reaction.

Secondary pozzolanic reactions of activated tailings (**Fig. 7**):



$$SiO_2 + xCa(OH)_2 + yH_2O \rightarrow C-S-H \quad (2)$$

$$Al_2O_3 + xCa(OH)_2 + yH_2O \rightarrow C-A-H \quad (3)$$

Fig. 7. Secondary pozzolanic reactions.

Ultrafine tailings physically fill the capillary voids between cement grains. Notably, even chemically inert tailings can accelerate cement hydration kinetics [39,40]. Their large specific surface area provides abundant heterogeneous nucleation sites, which effectively reduces the nucleation energy barrier for hydration products [41]. Consequently, this mechanism accelerates the nucleation and growth stage of cement hydration, significantly shifting the main hydration heat peak toward earlier ages.

At later ages, pozzolanic reactions become increasingly important in tailings-containing blends, although continued OPC hydration, filler effects, and pore-structure evolution may still contribute substantially. Reactive amorphous silica and alumina in the activated tailings dissolve in the highly alkaline pore solution, consuming portlandite and thereby modifying the phase assemblage of the hydration products. Mawire et al. [42] demonstrated that even slow-reactive tailings can incorporate selected elements into hydration phases, thereby altering the hydration pathways. Furthermore, this pozzolanic process consumes calcium while simultaneously releasing additional silicon and aluminum, significantly reducing the Ca/Si molar ratio of the primary C-S-H gel. A lower Ca/Si ratio promotes extensive aluminum substitution for silicon. This process transforms conventional fibrillar C-S-H into a foil-like C-(A)-S-H gel network. The resulting network is denser and more extensively polymerized. This microstructural evolution promotes the densification of the interfacial transition zone (ITZ).

Different tailings types also exhibit distinct synergistic hydration behavior. For instance, Geng et al. [43] observed the synergistic co-precipitation of ettringite and C-S-H gel in molybdenum tailings systems. Early-stage physical filling and late-stage gel precipitation act together to continuously refine the capillary pore network. This process improves both the mechanical strength and impermeability of concrete. To maximize these microstructural benefits without incurring severe clinker dilution, Johansson et al. [44] recommended controlling the replacement ratio strictly between 5% and 25%.

Overall, the hydration process of tailings-based SCMs involves a spatiotemporally coupled synergistic mechanism involving both physical and chemical effects, rather than a single chemical process. At early ages, physical filling and heterogeneous nucleation may partially compensate for clinker dilution at appropriate replacement levels, whereas excessive replacement still reduces the amount of reactive clinker and weakens early strength development. Meanwhile, late-stage pozzolanic reactions restructure the capillary pore network by precipitating dense gels with low Ca/Si ratios and complex phase assemblages. This continuous microstructural densification links microscopic phase evolution to macroscopic material performance. Ultimately, this mechanism supports the potential transformation of selected tailings into useful low-carbon cementitious constituents, provided that reactivity, durability, environmental safety, and activation impacts are validated.

3.2. Fresh properties

The incorporation of untreated tailings generally impairs fresh-state workability and increases water demand. Fluidity, yield stress, and plastic viscosity are critical indicators for evaluating the early-stage workability of these mixtures. Although high-range water-reducing admixtures or pre-wetting treatments can partially mitigate these rheological deficiencies, the irregular particle morphology of tailings still induces substantial rheological deterioration, thereby requiring careful adjustment of water content and admixture dosage to prevent severe slump loss. In addition, the relatively high specific surface area of tailings increases the demand for free water and intensifies interparticle friction, which further weakens the lubrication effect within the paste system.

Chen et al. [45] reported this adverse rheological effect when replacing fly ash with gold tailings in grouting materials. As the replacement ratio increased from 0% to 100%, the initial flowability decreased from 322 mm to 297 mm, still satisfying the requirements of the Chinese industry standard JG/T 408-2019. However, the mixture exhibited a pronounced loss of flowability within just 30 min, decreasing to 242 mm at 100% replacement (**Fig. 8**). While this example specifically highlights the rapid rheological loss in gold tailings-based grouts, similar mechanisms can be expected in broader cementitious mixtures. The extent of this flowability reduction depends strongly on the specific binder system, the material being replaced, particle morphology, and overall mixture compatibility. Specifically, it is essential to distinguish the reference material in these comparisons: replacing fly ash primarily removes the lubricating ball-bearing effect, whereas replacing cement mainly alters particle packing, clinker dilution, and admixture demand.

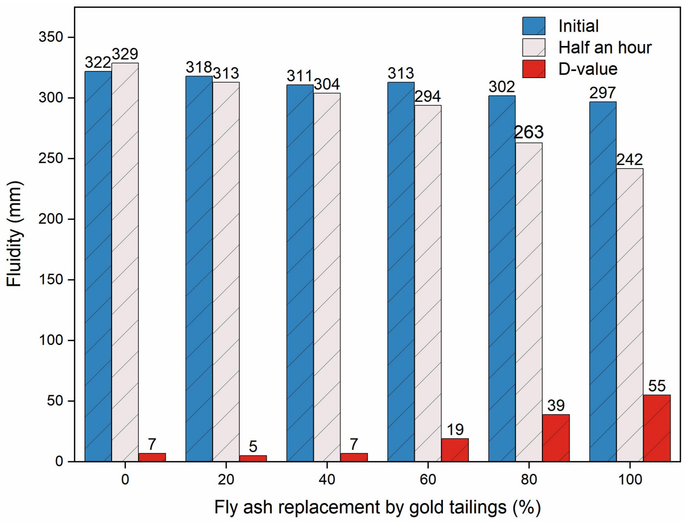


Fig. 8. Initial fluidity, half-hour fluidity, and fluidity loss (D-value) of grouting materials with different replacement ratios of fly ash by gold tailings [45].

To mechanistically explain this rapid slump loss, tailings particle morphology should be interpreted using the water film thickness (WFT) theory. Fly ash is primarily composed of glassy spherical particles that provide a lubricating ball-bearing effect. In contrast, after mechanical grinding activation, tailings particles exhibit highly irregular geometry and rough surface textures. Compared with relatively regular OPC clinker particles, this irregular particle morphology increases the internal friction resistance between particles. Furthermore, their specific surface area can be substantially higher than that of fly ash, resulting in higher free-water demand [46]. Consequently, the water film coating the solid particles becomes significantly thinner. This reduction in thickness escalates interparticle friction, suppresses the ball-bearing effect associated with spherical particles, and impairs overall flowability. Fundamentally, this macroscopic rheological deterioration is governed by WFT. As demonstrated by Zhu et al. [47], a reduction in WFT has an exponential negative impact on the spread diameter and flowability of tailings-based pastes.

Beyond simple flowability, the dynamic rheological behavior of tailings mixtures is governed by Bingham fluid parameters. In a dedicated study on tailings slurry rheology, Wang et al. [48] identified a distinct double-30 threshold: a particle size of 30 μm and a substitution level of 30% together constitute a critical transition threshold. When the tailings content exceeds 30%, particle flocculation progressively dominates the rheological behavior, leading to a sharp increase in the yield stress and internal frictional resistance of the slurry. However, this threshold requires further validation before it can be generalized in cementitious systems. Furthermore, Guo et al. [49] revealed that ultrafine tailings significantly alter the thixotropy and static yield stress of the fresh paste, confirming that high-volume tailings incorporation requires careful rheological mitigation.

Time-dependent rheological deterioration is further exacerbated by competitive adsorption mechanisms. Irregular tailings surfaces, particularly those containing clay-like or layered minerals, provide abundant adsorption sites. Liu et al. [50] explored this competitive mechanism, noting that tailings rapidly adsorb polycarboxylate ether (PCE) superplasticizer molecules through electrostatic interactions. Premature consumption of PCE molecules prevents them from providing the necessary steric hindrance for the cement grains, which leads to rapid agglomeration and severe slump loss. At this early stage, pozzolanic reactions have not yet been initiated, meaning no secondary hydration products are available to compensate for the deteriorating paste structure.

Tailings can also prolong the cement setting time. For instance, Deng et al. [51] observed that a 30% gold tailings replacement prolonged the final setting time from 186 to 213 min. The net effect of tailings on setting behavior is governed by competing mechanisms. While the irregular surfaces of tailings provide additional sites for heterogeneous nucleation, which can accelerate early hydration, this accelerating effect may be overshadowed by clinker dilution and increased water demand. To achieve normal consistency, additional mixing water is typically required. However, at high replacement levels, this excess free water dilutes the highly alkaline pore solution and delays ionic supersaturation. Combined with the limited early-age reactivity of the tailings, the time required for Ca^{2+} ions to reach supersaturation is prolonged, leading to extended setting times. Consequently, the nucleation of primary C-S-H gel is delayed, thereby extending the time required for the paste to lose plasticity and develop into a hardened structure. This macroscopic evolution is consistent with the early-stage observations reported by Wang et al. [52].

In summary, the influence of mine tailings on fresh cementitious systems primarily stems from their distinctive particle morphology and surface physicochemical properties. Elevated interparticle friction, reduced water film thickness, and competitive adsorption of polycarboxylate-based superplasticizers often lead to rapid slump loss and increased yield stress, and they may prolong setting time when dilution and additional water demand outweigh heterogeneous nucleation effects. However, standardized protocols for mitigating these early-stage rheological deficits are still lacking, highlighting the need for future research to develop tailored superplasticizers and robust mix-design guidelines specifically for highly irregular tailings. Without such optimization, the long-term performance benefits associated with subsequent pozzolanic reactions and microstructural densification cannot be fully realized.

3.3. Mechanical performance

The mechanical properties of tailings as SCMs are fundamentally governed by the coupled effects of particle packing optimization, micro-aggregate filling behavior, pozzolanic reactivity, and clinker dilution. Therefore, the feasibility of utilizing tailings as SCMs depends not only on their intrinsic physicochemical characteristics, but also on the rational optimization of mixture proportion design.

For many OPC-based systems reported in the literature, moderate replacement levels, often around 5%-25%, tend to balance filler/pozzolanic benefits against clinker dilution, but the optimum is mixture-specific. Within this range, compressive strength can equal or even surpass that of the plain cement control. To evaluate the suitability of different tailings as supplementary cementitious materials, Figueiredo et al. [53] compared sand mining tailings (ST), metakaolin (MK), and quartzite tailings (QT) as partial cement replacements. As shown in **Fig. 9**, all three materials improved the mechanical performance of hardened pastes, with the most significant enhancements observed at replacement levels of 7–14%. Among them, ST exhibited the greatest strengthening effect, increasing the compressive strength from 41.7 MPa for the reference mixture to 57.9 MPa at a 7% replacement level. The MK and QT mixtures also achieved compressive strengths exceeding 50 MPa, reaching maxima of 51.9 MPa and 52.0 MPa, respectively. Tensile strength followed a comparable trend, with peak values of 3.9 MPa for ST, 3.7 MPa for MK, and 3.5 MPa for QT. These results suggest that appropriately dosed tailings can effectively enhance both compressive and tensile performance when used as supplementary cementitious materials.

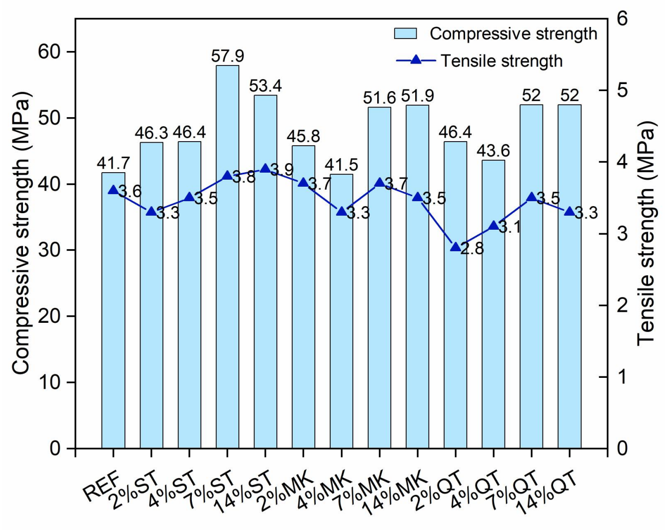


Fig. 9. Compressive and tensile strength at 28 days [53].

The dosage-dependent strengthening behavior has been extensively investigated in various types of tailings. Wang et al. [54] reported an inverted-U-shaped trend in both compressive strength and alkali resistance, as the gold tailings dosage increased from 5% to 15%, with performance peaking at a dosage of 10%. At this replacement level, the micro-filling effect and the pozzolanic reaction achieved optimal synergy, promoting the formation of C-S-H gel to the greatest extent and thereby optimizing the macro-scale mechanical performance.

Microstructural investigations also provide a mechanistic explanation for this dosage-dependent behavior. Using multi-scale characterization methods, including TGA, MIP, and SEM, Cui et al. [55] identified a 20% optimal substitution threshold. Their findings confirmed a dual enhancement mechanism: the fine tailings particles provide effective heterogeneous nucleation sites while actively driving secondary pozzolanic reactions. This synergy refines the pore structure and significantly densifies the cementitious matrix. Chen et al. [56] reached similar conclusions, showing that the incorporation of an appropriate tailings dosage reduced the total porosity and enhanced the continuity of hydration products, thereby improving the compressive strength and elastic modulus.

In addition to enhancing compressive strength, the appropriate incorporation of tailings can also improve the durability-related mechanical stability of cementitious materials. Zhang et al. [57] demonstrated that pore structure refinement induced by tailings particles effectively reduced chloride ion permeability and sulfate attack susceptibility, thereby contributing to superior long-term mechanical stability of the cementitious matrix. Similarly, Yao et al. [58] demonstrated that an optimized tailings dosage enhanced resistance to alkali–silica reaction

(ASR) and reduced permeability through progressive matrix densification. Collectively, these findings suggest that the mechanical enhancement induced by tailings incorporation is intrinsically linked to pore structure evolution and hydration product development.

However, the beneficial effects of tailings incorporation exhibit a distinct upper limit. As noted by Li et al. [59], once the replacement ratio exceeds the critical threshold, the deleterious dilution effect progressively dominates the hydration process. This excessive substitution substantially reduces the reactive clinker fraction and severely disrupts the optimal particle packing of the matrix. In simple OPC replacement systems without supplementary Ca or alkali sources, excessive substitution reduces available clinker-derived calcium and may inhibit pozzolanic reactions. Consequently, unreacted tailings particles act as inert filler phases within the matrix. This phenomenon increases internal porosity and weakens matrix integrity. Martins et al. [60] reported a similar trend, demonstrating that high-volume tailings substitution retarded hydration kinetics and markedly suppressed later-age strength development. Accordingly, the tailings replacement level should not be regarded as an arbitrary empirical variable, but rather as a system-specific threshold governed by the balance between hydration enhancement, particle packing, and clinker dilution. Below this threshold, tailings predominantly function as reactive micro-fillers that promote hydration and refine the pore structure. In contrast, excessive incorporation progressively weakens matrix continuity and mechanical integrity owing to insufficient cementitious reactivity.

Importantly, recent studies have shown that activation strategies can partially mitigate these limitations. Chen et al. [61] demonstrated that mechanical grinding, thermal activation, and alkali activation significantly enhanced the reactivity of gold tailings by destabilizing stable crystalline phases and increasing the content of amorphous reactive components. These activation approaches facilitate the transformation of tailings from relatively inert fillers into hydraulically active cementitious precursors, thereby extending their effective replacement range and improving the sustainability potential of cement-based systems.

Overall, the influence of tailings on the mechanical performance of cementitious materials exhibits a typical dosage-dependent response. Elucidating this threshold behavior and determining the optimal incorporation range for different tailings types are essential prerequisites for the large-scale engineering application of tailings-based SCMs. However, simply optimizing the mixture proportion cannot by itself overcome this dosage limitation. To safely exceed this replacement threshold and achieve large-scale utilization, it is imperative to fundamentally enhance the intrinsic pozzolanic reactivity of raw tailings through targeted activation strategies, as discussed in the next section.

4. Activation technologies for tailings

Due to their inherently limited pozzolanic reactivity and the potential presence of harmful impurities, raw tailings are unsuitable for direct incorporation at high clinker replacement levels. Consequently, systematic pretreatment and activation strategies are imperative to unlock their latent reactivity while minimizing potential environmental risks [62].

As illustrated in **Fig. 10**, the pretreatment and modification of SCMs follow a clear hierarchical progression based on increasing energy consumption and overall processing cost. While basic physical treatments, such as drying and comminution (Stages 1 and 2), serve as key prerequisites to increase the specific surface area of mine waste, unlocking the pozzolanic reactivity of stable crystalline tailings often necessitates higher-energy interventions, such as chemical wet treatments or thermal calcination (Stages 3 and 4). Although melt vitrification (Stage 5) offers maximum amorphization, its application in bulk tailings utilization is practically constrained by prohibitive economic and ecological costs. Building upon this multi-stage technological gradient, mainstream activation strategies for mine tailings can be broadly classified into mechanical, thermal, chemical, and combined activation [63]. Recent theoretical and experimental advancements regarding the activation mechanisms and process optimizations for various tailings are systematically summarized in **Table 3**.

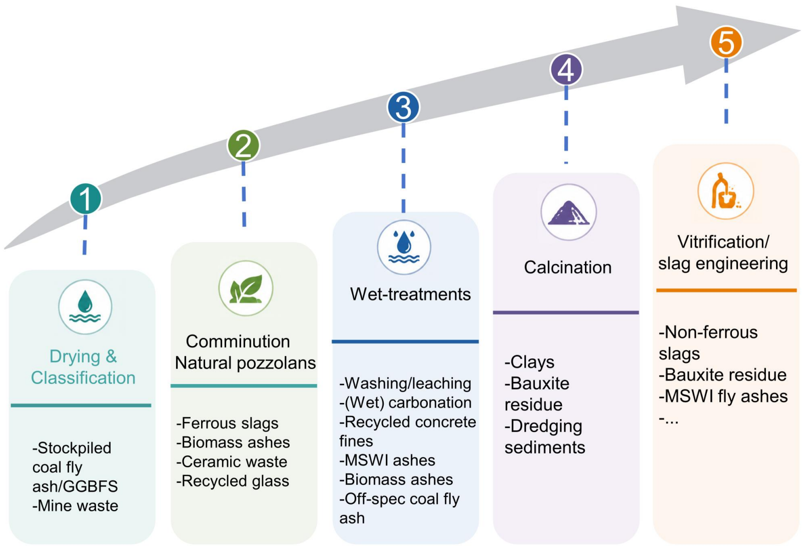


Fig. 10. Mainstream pretreatment and modification system for supplementary cementitious materials (sorted by energy consumption. and cost in ascending order)

Table 3. Studies on activation methods for different tailings types.

Researchers	Tailings	Activation methods	Main Research Contents

	types		
Wang et al. [64]	Vanadium tailings	Mechanical activation	It increased the 28-day compressive strength of the material to 15 MPa.
Cao et al. [65]	Gold tailings	High-temperature thermal activation	Thermal activation can significantly improve the pozzolanic activity of gold tailings, and a thermal activation temperature range of 800–900 ℃ is recommended.
Zhao et al. [66]	Iron tailings	Activation with a composite activator of NaOH and $CaSO_4 \cdot 2H_2O$	When the dosage of the composite activator is 2.5%, the 28-day compressive strength of the mortar reaches 57.5 MPa, and the activity index increases to 89%.
Wang et al. [67]	Garnet tailings	Mechanical activation	After mechanical activation, its pozzolanic activity was tested. The results show that the 28-day activity index increased from 54.43% to 82.67%, confirming a significant improvement in activity.
Xu et al. [68]	Copper tailings	Chemical activation	NaOH and Na_2CO_3 significantly promote the dissolution of CTs and effectively improve the performance of AAC.
Zheng et al. [69]	Copper tailings	Wet grinding activation	A 20-minute wet grinding process refined the median particle size to 4.49 μm; at 20% replacement, the 28-day compressive strength reached 50.9 MPa, outperforming the pure cement baseline of 44.2 MPa.

4.1. Mechanical activation

Mechanical activation applies intense shear, impact, and grinding forces through ball milling, high-energy milling, or disc milling to refine particle size and increase specific surface area. More importantly, it can disrupt the crystalline structure by introducing lattice defects and reducing structural order, while in some cases increasing the proportion of amorphous and highly reactive phases. The effectiveness of mechanical activation is strongly influenced by the grinding environment (e.g., dry or wet grinding) and milling duration. As summarized in **Table 4**, wet-ground iron ore tailings (WIOTs) exhibited substantially greater particle refinement and surface area development than dry-ground iron ore tailings (DIOTs). For instance, after 60 min of wet grinding, the median particle size (d_{50}) decreased from 80.498 μm to 6.203 μm. Correspondingly, the compressive strength increased from 32 MPa to 39 MPa, indicating a substantial improvement in the reactivity of the activated tailings.

Table 4. Particle size distribution and physical properties of iron ore tailings under different grinding conditions [70].

	d_{10}	d_{50}	d_{90}	Compressive Strength (MPa)
RIOTs	19.375	80.498	243.706	/
DIOTs30	2.041	22.793	66.979	32
DIOTs60	2.114	22.738	53.787	33.5
WIOTs30	1.578	8.334	18.055	36.5
WIOTs60	0.976	6.203	15.935	39

Similarly, Hernandez-Ramos et al. [71] evaluated the mechanical activation of gold-silver tailings (GST). X-ray diffraction (XRD) demonstrated that a 140-minute ball milling process effectively reduced both crystallite and macroscopic particle sizes. To assess their cementitious potential, mortars incorporating the mechanically activated GST (ACT-MEC-GST) and a 1000 ℃ thermally activated sample (ACT-THER-GST) were benchmarked against an OPC control. As shown in **Fig. 11**, while partial cement substitution caused a slight strength reduction relative to the OPC control mortar, the 28-day compressive strength of both activated tailings mortars exceeded the ASTM C270 minimum requirement. These findings indicate that while the resulting strength remains lower than the OPC control, mechanical comminution alone can sufficiently activate these metallic tailings to meet minimum mortar requirements, offering a more energy-efficient alternative to high-temperature thermal treatments.

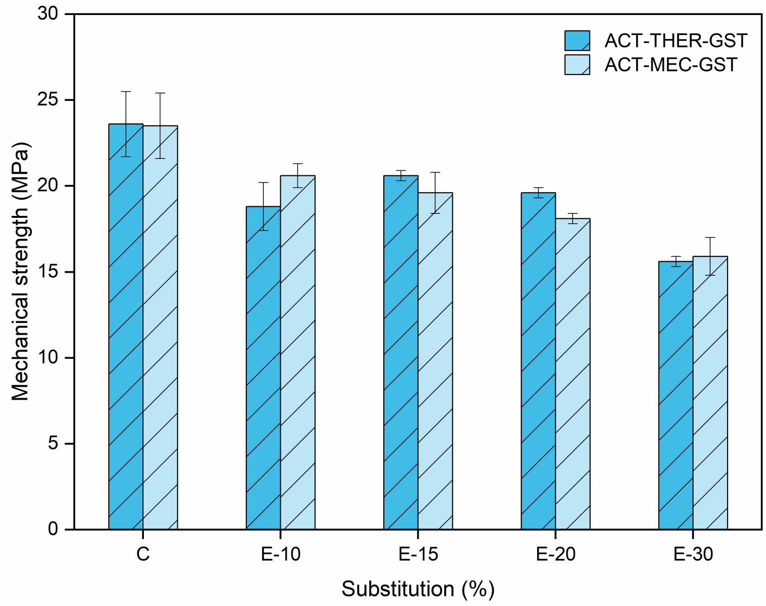


Fig. 11. Unconfined compressive strength of control mortar cubes and experimental mortar cubes substituted with ACT-MEC-GST and ACT-THER-GST [71].

4.2. Thermal activation

Thermal activation enhances the latent pozzolanic reactivity of tailings through controlled calcination. This endothermic process typically induces the dehydroxylation of clay minerals and the thermal decomposition of sulfides. These changes alter the mineralogical composition, disrupt long-range crystalline order, and generate highly reactive amorphous phases. In sulfide-bearing tailings, these transformations can further enhance pozzolanic activity. However, thermal activation may also lead to gas emissions, the formation of sulfate-bearing products, and sintering phenomena. Consequently, assessments of thermal activation should consider not only reactivity enhancement but also gas-emission control, phase evolution, and environmental safety. While this technology is particularly effective for clay-rich or sulfide-bearing tailings, the optimal calcination temperature strongly depends on the mineralogical characteristics of the feedstock.

For tailings dominated by thermally unstable minerals such as kaolinite, the required activation energy is relatively low. For instance, Zhou et al. [72] investigated the cementitious activity of bauxite tailings and identified 700 °C as the optimal thermal activation threshold for complete dehydroxylation of diaspore and kaolinite. Vargas et al. [73] selected eight copper tailings from distinct geological sources to systematically delineate their thermal activation behavior. They observed that while significant chemical modifications occurred across a broad 500-900 ℃ spectrum, the optimal pozzolanic reactivity was tightly concentrated within the 600-800 ℃ window. However, this optimal temperature range is strictly dictated by the specific mineralogy of these particular samples and cannot be indiscriminately generalized as a universal baseline for all copper residues, let alone other tailings types.

Conversely, tailings dominated by more stable crystalline networks require substantially higher thermal energy to disrupt their lattices. For instance, Cao et al. [65] conducted a comprehensive study on the microstructural reconstruction of gold tailings and demonstrated that a calcination temperature of 800-900 °C was required to maximize their pozzolanic activity. Recent studies on lead-zinc tailings further corroborated that their complex mineralogy necessitates elevated calcination temperatures. As detailed in **Table 5**, the experimental results revealed a clear relationship between calcination temperature, mass loss, and mechanical performance. Mass loss increased progressively with temperature, reaching 3.7% at 800 °C, suggesting substantial mineral decomposition and structural modification. Correspondingly, both compressive strength and the strength activity index (SAI) reached their maximum values of 40.5 MPa and 79.0%, respectively. However, further increasing the calcination temperature to 900-1000 °C resulted in a noticeable decline in strength, with compressive strength decreasing to 32.5 MPa at 1000 °C. This reduction was likely associated with over-calcination, which may induce sintering and the formation of less reactive crystalline phases. Optimization experiments demonstrated that an activation temperature of 900 ℃ coupled with a 30-minute holding time successfully stimulated the latent pozzolanic reactivity of lead-zinc tailings, enabling the formulated cementitious materials to achieve a 28-day compressive strength of 20 MPa [74].

Table 5. Influence of thermal treatment temperatures on the physical and mechanical properties of gold tailings[65].

Temperature (℃)	Mass loss (g)	Mass loss rate (%)	Compressive Strength (MPa)	Strength Activity Index (%)
25			36.0±1.0	71.0
500	15.5±2.0	1.6	37.5±1.0	73.0
600	27.5±1.0	2.7	38.0±1.0	74.5
700	35.0±2.0	3.4	38.5±1.0	75.0
800	38.0±2.5	3.7	40.5±1.0	79.0
900	39.0±1.0	3.8	38.5±1.0	75.0
1000	39.5±1.5	3.9	32.5±1.5	63.5

Determining the appropriate activation temperature requires careful optimization. Suboptimal temperatures yield incomplete phase transformation and negligible activation. Conversely, excessive heating induces particle sintering and deleterious recrystallization, which destroys the microporosity and substantially reduces the specific surface area. Lemma et al. [75] reported that thermal activation beyond the optimal temperature (e.g., beyond

800 ℃ for chlorite-bearing phases) can induce severe structural collapse and particle agglomeration through sintering, thereby significantly diminishing the pozzolanic reactivity of the material. More importantly, the indiscriminate application of thermal activation without prior rigorous mineralogical characterization is both energetically wasteful and ineffective in improving mechanical performance. For instance, Lei et al. [76] demonstrated that basalt tailings achieve optimal geopolymerization reactivity in their raw, uncalcined state. Applying a 750 ℃ thermal pretreatment yielded only marginal mechanical benefits, culminating in a low compressive strength of 7 MPa and a high matrix porosity of 30%.

4.3. Chemical activation

Chemical activation utilizes targeted reagents to destabilize the Si–O–Si and Si–O–Al covalent bonds within the aluminosilicate framework of tailings, thereby accelerating the dissolution of reactive phases, the release of active species, and their subsequent repolymerization into cementitious products. Depending on the nature of the activating reagent, chemical activation can generally be classified into acid, alkaline, and salt-assisted approaches. Alkaline activation operates under highly alkaline conditions, where hydroxyl ions (OH^-) aggressively attack aluminosilicate structures and promote the formation of dense binding gel networks. In contrast, acid activation relies on proton (H^+) attack to dissolve metallic cations and generate a highly porous, silica-rich framework, although its application in bulk construction materials remains limited because of its corrosive nature. Salt activation typically occurs under neutral or mildly modified pH conditions. Rather than inducing extensive dissolution, it provides specific anions (e.g., SO_4^{2-}) that react with dissolved aluminate species to form secondary strength-enhancing mineral phases. Although the underlying mechanisms differ, all three approaches are fundamentally linked by their ability to reduce the activation energy barrier of inert tailings and enhance their reactivity.

Currently, the combined use of NaOH and Na_2SiO_3 represents one of the most widely adopted alkaline activation strategies. NaOH promotes the dissolution of aluminosilicate phases, while Na_2SiO_3 supplies soluble silicate species that facilitate gel formation. The synergistic effect of these activators has been demonstrated in vanadium tailings-based geopolymers [77]. A mixture containing 3% NaOH and 3% Na_2SiO_3 achieved the highest 28-day compressive and flexural strengths of 31.9 MPa and 4.98 MPa, respectively, significantly outperforming systems activated by either reagent alone (**Table 6**).

Table 6. Effect of different alkaline activators on compressive strength [77].

	Compressive Strength (MPa)			Flexural Strength (MPa)		
	3 days	7 days	28 days	3 days	7 days	28 days
6% NaOH	9.3	11.3	13.3	3.65	3.70	4.20
6% Na_2SiO_3	8.9	9.8	11.5	2.00	2.56	3.10
4% NaOH + 2% Na_2SiO_3	12.4	19.3	21.8	3.25	3.70	4.07
2% NaOH + 4% Na_2SiO_3	14.0	16.1	19.7	2.60	3.04	3.62
3% NaOH + 3% Na_2SiO_3	23.8	28.8	31.9	4.15	4.47	4.98

Xu et al. [68] evaluated diverse alkaline activators for copper tailings-based autoclaved aerated concrete (AAC). Their findings confirmed that NaOH and Na_2CO_3 outperformed other agents by simultaneously accelerating hydration kinetics and refining the macroscopic pore structure. Under optimized NaOH activation, the AAC achieved a compressive strength of 3.85 MPa, a bulk density of 605 kg/m^3, and a thermal conductivity of 0.135 W/(m·K). These parameters satisfy the Grade B06 A3.5 structural and thermal requirements specified in the Chinese standard GB/T 11968-2020. Similarly, Wei et al. [78] deployed NaOH to activate low-silica molybdenum tailings for AAC production. Their study mapped the kinetic evolution across the entire hydration-hydrothermal process. During early ambient hydration, strong alkalinity accelerated mineral dissolution. This process precipitated abundant C-S-H gel and refined the initial pore network. In the subsequent autoclave stage, NaOH catalyzed a crucial crystallographic transformation by converting metastable C-S-H into highly crystalline tobermorite, which directly influenced macro-scale mechanical performance. Increasing the NaOH dosage to an optimal 1.5% elevated the compressive strength from 1.8 MPa to a peak of 4.3 MPa. These optimized blocks fully satisfied the structural requirements of the Chinese GB/T 11968-2020 standard. However, an excessive activator dosage exceeding 2.0% triggered a marked decrease in strength to 2.6 MPa. The residual unreacted alkali induced deleterious alkali-aggregate reactions (AAR) and caused substantial microstructural deterioration. While these AAC studies demonstrate the effectiveness of alkaline activation in autoclaved tailings-based products, their implications for OPC-based systems should be evaluated separately.

To overcome the limitations of single reagents, multi-component activators offer synergistic advantages. Zhao et al. [66] formulated a NaOH-$CaSO_4 \cdot 2H_2O$ composite activator to stimulate iron tailings. X-ray photoelectron spectroscopy (XPS) analysis indicated changes in the chemical environments of Si, Al, and Ca, suggesting a partial weakening or restructuring of the Si-O, Al-O, and Ca-O bonds, reducing the binding energies of the Si_{2p}, Al_{2p}, and Ca_{2p} orbitals to 102.45 eV, 73.95 eV, and 346.76 eV. This significant lattice destabilization exposed abundant reactive sites, consequently increasing the specific surface area of the activated tailings to 237.5 m²/kg and increasing the amorphous phase content to 43.87%. **Fig. 12** illustrates the development of compressive and flexural strengths across 3, 7, and 28 days of curing under varying composite activator dosages. An optimal composite dosage range of 2.5-3.0 wt% maximized the 28-day compressive strength at 57.5 MPa, achieving a high activity index of 89%. Conversely, excessive dosages (e.g., 5.0 wt%) induced local AAR and uneven product distribution, resulting in severe microstructural degradation and strength regression. Furthermore, a life cycle assessment demonstrated that this optimized composite matrix reduced the global warming potential (GWP) by 25.7% compared with plain OPC counterparts.

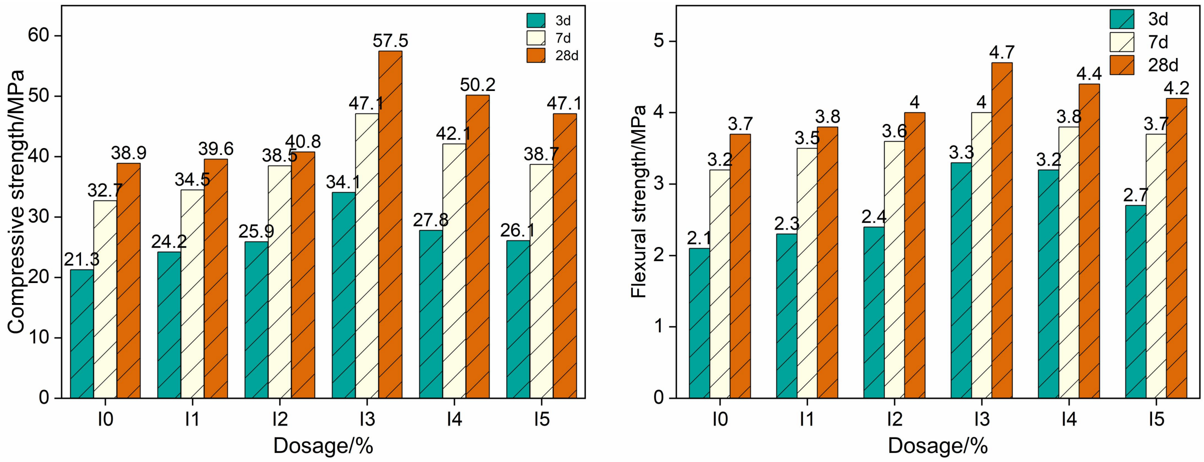


Fig. 12. Effect of different composite activator dosages on the strength of iron tailings [66].

4.4. Composite activation

While single activation methods effectively enhance tailings reactivity, they suffer from inherent limitations such as high energy consumption, marginal efficiency, and restricted mechanisms. Consequently, synergistic composite activation has emerged as a promising strategy for maximizing reactivity enhancement through complementary activation mechanisms.

For mechanochemical coupling, Zhang et al. [79] integrated intense mechanical grinding with alkaline chemical activation to treat low-activity iron tailings. Mechanical force physically fragments the dense crystalline networks, simultaneously increasing the specific surface area and introducing abundant lattice defects. Because these defects act as preferential dissolution zones for chemical activators, the pozzolanic reaction can propagate deep into the particle core, resulting in a substantial enhancement in cementitious activity. Yang et al.

[80] proposed a sulfate-assisted wet-grinding mechanochemical activation strategy to enhance the reactivity of iron tailings powder. By comparing the effects of calcium sulfate dihydrate (CaSO4·2H2O) and sodium sulfate (Na2SO4), the authors identified distinct activation pathways, as reflected by the compressive strength development shown in **Fig. 13**. The results indicated that Na2SO4 primarily promoted early-age strength development. In particular, the addition of 3% Na2SO4 (Na3W) increased the 3-day compressive strength from 15.1 MPa for the control sample (W0) to 24.9 MPa. This dosage also provided the most balanced performance, avoiding the decline in 28-day strength observed at the higher dosage of 5% (Na5W). In contrast, CaSO4·2H2O produced a more gradual but sustained enhancement of reactivity, with the 3% dosage (Ca3W) achieving the highest 28-day compressive strength of 45.5 MPa. The enhanced performance was attributed to the synergistic interaction between mechanical and chemical activation. Wet grinding effectively reduced particle size and disrupted the crystalline structure of the tailings, whereas sulfate additives promoted the cleavage of Si–O and Al–O bonds. As a result, a greater proportion of amorphous reactive phases was generated, thereby improving the overall reactivity of the tailings.

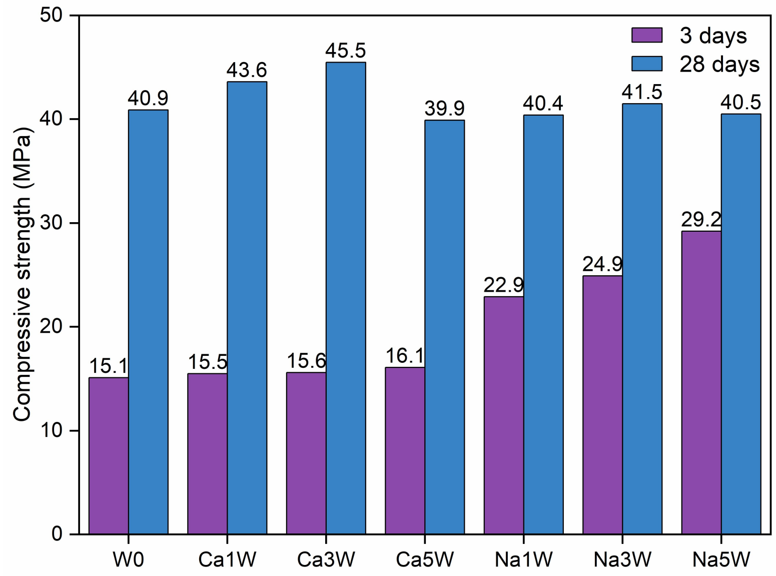


Fig. 13. Compressive strengths of cement-ITP composites [80].

Hu et al. [81] further developed a synergistic activation process combining mechanical grinding with alkali-siliceous chemical activation, and investigated the regulatory effects of two activators, Na_2SiO_3 and $Ca(OH)_2$, on the hydration and hardening behavior of iron tailings-based SCM systems. Their results showed that mechanical activation pre-disrupted the dense crystal structure of iron tailings and exposed numerous active sites. On this basis, the introduced chemical activators exerted dual synergistic effects, promoting the pozzolanic reaction to propagate toward the particle core. The synergistic effect of increased hydration products and a densified microstructure substantially improved both early- and late-age (28 d and beyond) compressive strength of the specimens.

Beyond mechanochemical approaches, the coupling of thermal and mechanical activation also demonstrates significant synergistic benefits. For instance, Chen et al. [82] systematically evaluated the thermal-mechanical synergistic activation of coal gangue tailings. Their findings demonstrated that a moderate calcination temperature of 500-600 ℃ was sufficient to achieve the primary structural transformation of kaolinite into metakaolin. The resulting pozzolanic activity reached a reliably high level, enabling these tailings to be effectively utilized as SCMs in industrial cements.

Further evidence of this synergistic effect was provided by Li et al. [83], who systematically investigated the influence of composite activation parameters on the pozzolanic activity and mechanical performance of tailings (**Table 7**). As shown in Table 1, the untreated control tailings (CT) exhibited very limited reactivity, with an activity index of only 5.06. In contrast, composite activation (TCT series) markedly enhanced tailings reactivity. Among all mixtures, TCT-80 achieved the highest activity index of 89.91. This improvement was directly reflected in the compressive strength development (**Fig. 14**), where TCT-80 consistently exhibited superior mechanical performance at all curing ages and exceeded 10 MPa after 28 days of curing. However, the results also revealed the existence of an optimal activation threshold. Excessive milling, as represented by TCT-100, reduced the activity index to 67.52 and led to a decline in late-age compressive strength. This deterioration was likely associated with particle agglomeration and the loss of effective reactive sites caused by over-grinding, highlighting the importance of optimizing composite activation parameters to maximize activation efficiency.

Table 7. Effect of composite activation on the activity index of tailings [83].

Samples	Mechanical milling (min)	Calcination (min)	Activity Index
CT	-	-	5.06
TCT	-	120	76.05
TCT-60	60	120	58.59
TCT-80	80	120	89.91
TCT-100	100	120	67.52

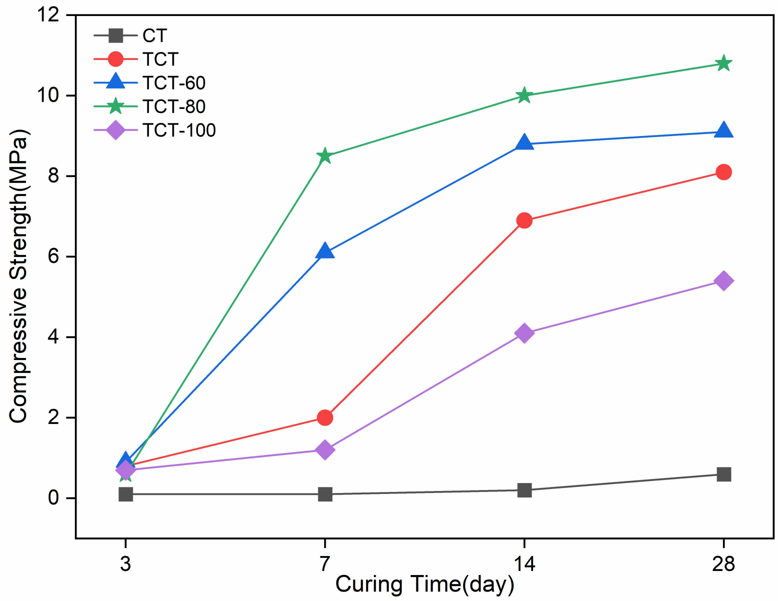


Fig. 14. Compressive strength of experimental materials with different conditions [83].

As research has progressed, multi-field coupled activation technology has gradually shown superior efficiency in enhancing reactivity. Li et al. [84] systematically investigated the effects of three single activation methods (mechanical, thermal, and chemical) and their different combinations on the physicochemical properties and reactivity of molybdenum tailings. The study confirmed that multi-method coupled activation produces a pronounced synergistic effect. Among these approaches, mechanical-thermal-chemical triple coupling activation achieved the best performance, increasing the activity index of molybdenum tailings by 34.1% compared with the raw sample and 16.8% compared with single mechanical activation. The preparation parameters of all specimens are summarized in **Table 8**. By systematically characterizing the physicochemical properties and cementitious reactivity of molybdenum tailings under different activation methods, the synergistic enhancement mechanism of multi-field coupled activation was elucidated.

Table 8. Preparation parameters of molybdenum tailings specimens under different activation regimes [84].

Samples	Mechanical milling (min)	CaO (%)	Calcination (min)
R	-	-	-
M	90	-	-
MT	90	-	60
MC	90	5	-
MTC	90	5	60

The 28-day compressive strength (σ) and strength retention ratio (S) of molybdenum tailings-based cementitious materials under different activation regimes are presented in **Fig. 15**. As shown, incorporation of raw tailings caused a sharp decrease in compressive strength from 45.5 MPa for the plain cement control to 27.0 MPa, corresponding to a strength retention of only 58%. With progressive improvement in activation mode, the mechanical performance progressively recovered: single mechanical activation (Group M) restored strength to 30.7 MPa (67% retention); mechanical-thermal coupling (Group MT) and mechanical-chemical coupling (Group MC) further increased strength to 32.3 MPa (71%) and 33.5 MPa (74%). The mechanical-thermal-chemical triple coupling activation (Group MTC) yielded the optimal performance, with compressive strength recovered to 35.7 MPa and strength retention reaching 78%. This represents an improvement of 34.5% relative to the raw Group R and 16.3% relative to the single mechanically activated Group M, which is consistent with the measured reactivity index results.

Composite activation can improve reactivity more efficiently than some single methods, but it does not automatically reduce energy demand. Multi-field coupled activation improves mechanical performance. However, evaluating it solely on mechanical metrics is incomplete. Approaches such as mechanical-thermal-chemical activation require prolonged grinding and high-temperature calcination, which are energy-intensive steps that carry substantial carbon burdens capable of offsetting the emissions saved by replacing cement clinker. Recent LCA studies warn that the true sustainability of these SCMs is determined by system boundaries. To ensure a net environmental benefit, the carbon emitted during activation must not exceed the carbon saved from clinker substitution and raw material transport. Therefore, future research must prioritize low-energy activation strategies coupled with comprehensive cradle-to-grave LCA modeling to fully account for long-term environmental impacts and durability.

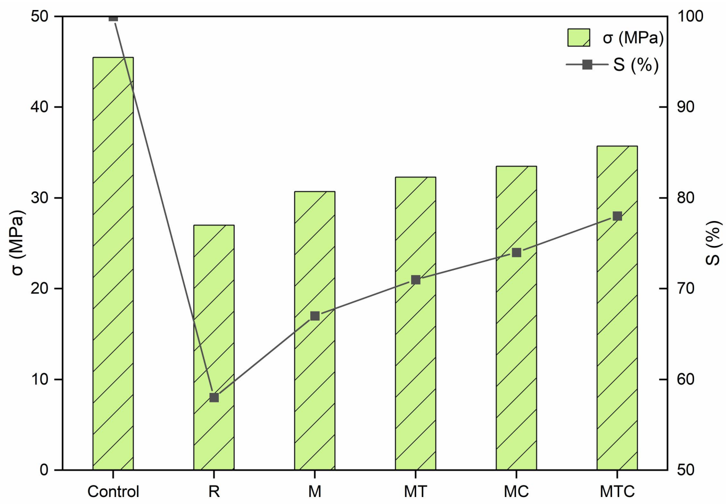


Fig. 15. 28-day compressive strength (σ) and strength retention rate (S) of molybdenum tailings-based cementitious materials under different activation methods [84].

Proper activation can significantly expand the feasible replacement range of tailings, while the optimal replacement level remains highly system-dependent, governed by tailings mineralogy, activation intensity, binder chemistry, and performance requirements. However, because this process exhibits diminishing efficiency, pushing mechanical or thermal inputs too far not only inflates costs but also triggers severe side effects, such as particle agglomeration and the precipitation of unreactive phases. Industrial scale-up cannot rely on excessively intensive activation. It demands a rigorous techno-economic evaluation to identify optimal parameters.

In summary, activation is an indispensable enabling strategy. It bridges the gap between the inert nature of raw tailings and the strict demands of high-performance SCMs. Tailored single-field or synergistic composite protocols successfully activate latent pozzolanic reactivity. This transformation provides a theoretical and material basis for the macroscopic engineering applications discussed next.

5. Case studies and comparative analysis on different tailings

Mine tailings are inherently heterogeneous materials whose physicochemical properties, latent pozzolanic activity, and environmental risks are dictated by the parent ore deposit and the specific extraction process. Consequently, a universal utilization strategy remains impractical. To bridge theoretical mechanisms with actual engineering practices, the following sections categorize tailings into three major groups based on mineralogy and industrial scale. These categories include iron tailings (massive reserves, inert crystalline phases), non-ferrous metallic tailings such as copper and gold (high siliceous reactivity, severe heavy metal risks), and other emerging industrial solid wastes.

5.1. Iron tailings

As one of the largest and most underutilized industrial solid waste streams globally, iron ore tailings represent a critical resource for decarbonizing the building materials sector, particularly in China, where their exceptional abundance offers significant potential for scalable valorization. These tailings are generated as a solid by-product during the beneficiation process, where mined ore undergoes sequential crushing, dry separation, wet grinding, and magnetic separation to isolate the iron concentrate. The remaining slurry, typically conveyed to tailings ponds for storage and disposal, consists primarily of SiO_2, Al_2O_3, and Fe_2O_3. With appropriate activation, this mineralogical profile allows iron ore tailings to serve as a promising, resource-rich candidate for SCMs, provided that activation, durability, and environmental safety are verified.

Amjad et al. [85] emphasized that the mineralogy of iron ore tailings is dominated by quartz, whose highly inert crystalline structure requires mechanical, chemical, thermal, or hydrothermal activation to stimulate their latent pozzolanic activity effectively. Iron ore tailings generally show mixture-specific optimum replacement levels. In simple OPC replacement systems, many studies indicate a practical limit near 20%, whereas mechanically activated or composite cement systems may tolerate 10%–30% replacement when specific performance requirements (such as Grade 32.5) are targeted.

Despite its widespread use, standalone mechanical activation still faces high energy consumption and limited reactivity gains. Yao et al. [86] demonstrated that extended grinding progressively depolymerizes the iron ore tailings crystal structure. In an alkaline environment rich in calcium oxide, this activated structure actively precipitates fibrous ettringite and amorphous C-S-H gel, with the Ca/Si ratio of these cementitious phases progressively decreasing over time to reach 0.84 at 28 days. This allows a 10%–30% iron ore tailings composite cement to fully meet the technical requirements of Grade 32.5 composite OPC specified in GB 175. Li et al. [87] successfully expanded this application to seawater-sea sand mortar (SSSM) systems. Untreated iron ore tailings substantially reduced compressive strength. By contrast, mechanically activated iron ore tailings interacted favorably with the highly alkaline and chloride-rich pore solution. They simultaneously promoted C-S-H gel crosslinking and immobilized free chlorides through the formation of Friedel salt. This dual action refined the pore structure and effectively mitigated strength attenuation in marine environments.

Recent research on the valorization of iron ore tailings reveals a clear technical evolution: moving from energy-intensive standalone mechanical activation to more efficient, multi-solid-waste synergistic systems. This synergistic approach can improve performance near the conventional replacement limit and may, in selected systems, enable higher solid-waste incorporation. However, replacement levels above 20% require direct validation. Goulart et al. [88] evaluated the partial replacement of cement with both slurry and dry iron ore tailings. They determined that iron ore tailings effectively promote the early hydration of aluminate phases through heterogeneous nucleation. While a 10% dosage of slurry iron ore tailings maintained early compressive strength, higher dosages or dry iron ore tailings slightly compromised late-age strength. Building upon this, Wang et al. [89] engineered an iron ore tailings-steel slag binary cementitious system. Their multi-scale characterization confirmed that targeted iron ore tailings incorporation chemically complements steel slag hydration. This synergy simultaneously maximizes compressive strength and chloride penetration resistance at the optimal dosage.

Zhang et al. [90] further developed a ternary SCM system composed of phosphorus slag, lithium slag, and high-silicon iron ore tailings. The independent effects of the IOTs fraction within the ternary SCM and the overall SCM replacement level on compressive strength development are illustrated in **Fig. 16**, respectively. As shown in **Fig. 16** (a), reducing the iron ore tailings fraction from 1.0 to 0.3 significantly increases the 28-day compressive strength from 35.6 MPa to 46.9 MPa, indicating that a lower tailings content promotes enhanced synergistic hydration interactions between phosphorus slag and lithium slag. Furthermore, when the optimized ternary SCMs are incorporated at different replacement levels (**Fig. 16** (b)), the compressive strength exhibits a characteristic inverted U-shaped trend. The maximum strength is achieved at a replacement level of 20%, where the 28-day compressive strength reaches 52.0 MPa, representing a 6.8% improvement compared with the plain cement control (48.7 MPa). Beyond this optimum level, the clinker dilution effect progressively outweighs the benefits of synergistic hydration, resulting in a reduction in 28-day compressive strength to 46.9 MPa at 30% replacement and further to 40.2 MPa at 40% replacement. Mechanistically, the optimized ternary SCM system effectively refines the pore structure and reduces the amount of unhydrated cement particles within the ITZ, thereby contributing to the observed strength enhancement.

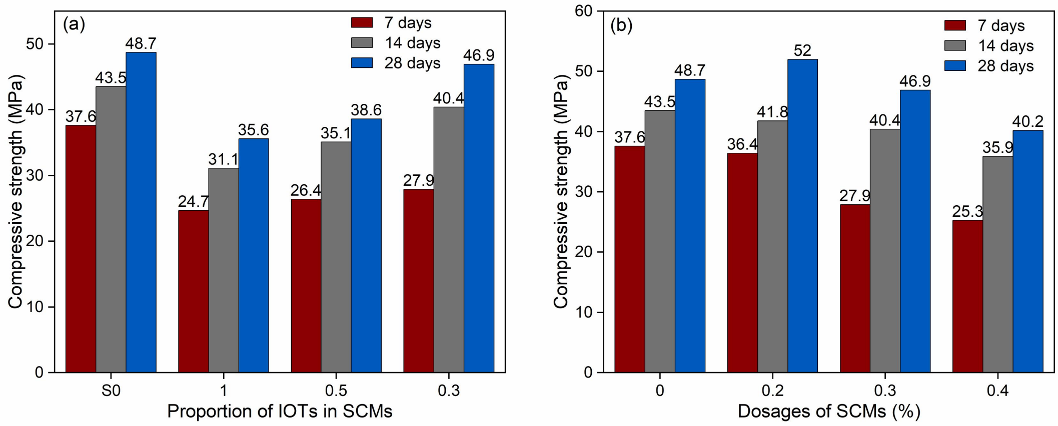


Fig. 16. Compressive strength of concrete: (a) proportion of IOTs in SCMs and (b) dosages of SCMs [90].

Recent breakthroughs have integrated iron ore tailings into limestone calcined clay cement (LC_3). When assessing the carbon-reduction potential of tailings-based LC_3 systems, it is necessary to distinguish among clinker reduction, binder replacement, and filler replacement. Zhang et al. [91] incorporated iron ore tailings as a tailings sand fraction within an LC_3-based system rather than as a reactive binder constituent (**Fig. 17**). The mixture achieved a 28-day compressive strength of 42 MPa, comparable to that of conventional OPC systems. Furthermore, relative to the benchmark LC_3 formulation, the system reduced OPC consumption by approximately 50%. Such comparisons should be interpreted with reference to the specific benchmark mixture employed, as the magnitude of OPC reduction depends on both the replacement strategy and the baseline composition. Microscopic analysis revealed that the reactive silicon-aluminum components in the iron ore tailings participated in the LC_3 hydration sequence to generate additional C-(A)-S-H gels. This participation refined the pore structure and significantly densified the ITZ. Ultimately, this LC_3 case should be presented as a combined clinker-reduction and tailings-filler strategy rather than direct evidence that reactive iron-tailings SCM replacement can exceed 20%.

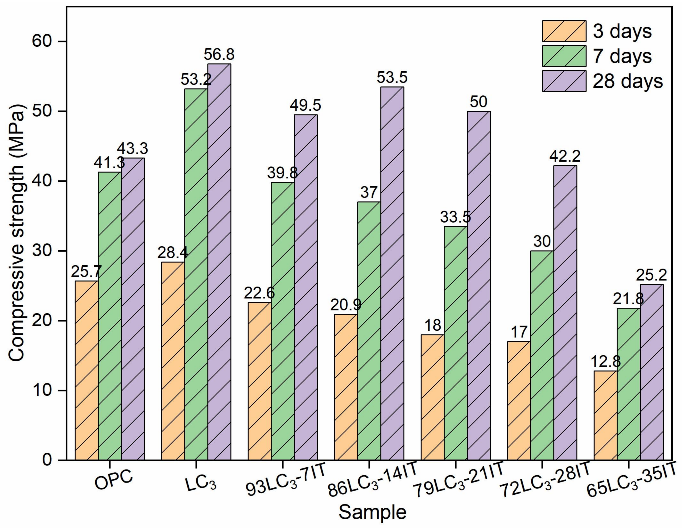


Fig. 17. Compressive strength development of LC_3 systems with different iron ore tailings contents at 3, 7, and 28 days [91].

While the microstructural densification and mechanical enhancement achieved through SCM incorporation are scientifically significant, the inherently limited replacement ratios imposed by clinker dilution necessitate a broader strategy. To maximize total solid waste diversion and achieve bulk consumption at the million-ton scale, recent research advocates for a complementary strategy: coupling SCM substitution with fine aggregate replacement. While incorporating these tailings as a natural sand alternative effectively improves concrete durability, the optimal replacement ratio heavily depends on grading, particle shape, and water demand. Furthermore, several studies suggest that conservative replacement levels (often below 25%) are required to avoid performance loss. The utilization of cement-stabilized iron ore tailings as road engineering materials represents a key technical pathway for achieving multi-million-ton-scale bulk consumption of these solid wastes. In this context, Khamseh et al. [92] systematically quantified the engineering properties of stabilized iron ore tailings. They found that a modest cement dosage of 5%–10% substantially mitigated the low strength and high compressibility inherent to raw iron ore tailings. This macroscopic improvement is driven by robust cementation and significantly enhanced cohesion. By establishing a direct quantitative link between compressive strength and the porosity-to-volumetric cement index, this research provides a rigorous technical foundation for applying cement-stabilized iron ore tailings in subbase layers.

In summary, reported activated iron ore tailings systems can meet selected mechanical requirements at replacement levels of approximately 10%–30%, depending on the binder system, activation route, curing regime, and target standard. When combined with other solid wastes such as steel slag and phosphorus slag, or integrated into advanced systems such as LC_3, they produce significant synergistic hydration effects. However, due to the high proportion of inert quartz, robust mechanical or multi-method composite activation remains strictly necessary. Overall, despite challenges such as high activation energy and the need for long-term durability data, these diversified technical pathways provide a solid foundation for the large-scale resource utilization of iron ore tailings.

5.2. Gold tailings and copper tailings

Iron ore tailings are predominantly composed of inert quartz. In contrast, many studied gold and copper tailings contain abundant siliceous or aluminosilicate phases, giving them potential pozzolanic value. However, their actual reactivity is controlled by amorphous content, mineral stability, activation state, and contaminant profile. When sufficient reactive aluminosilicate phases are present or appropriate activation is applied, these reactive powders undergo robust secondary pozzolanic reactions with $Ca(OH)_2$. This process precipitated abundant, highly dense C-(A)-S-H gel networks that effectively fill capillary pores and enhance mechanical interlocking within the ITZ. Therefore, as long as rheological degradation and environmental and toxicological risks are strictly controlled, these tailings function beyond conventional physical filler effects. They represent promising candidates for formulating high-performance SCMs. Ultimately, they deliver enhanced mechanical strength and durability to structural-grade building materials.

Maali et al. [93] provided a comprehensive review of the application of gold tailings in concrete and SCMs. Their review highlighted that gold tailings can be activated through mechanical, thermal, or composite treatments. When the cement replacement ratio is controlled between 5% and 30%, these tailings effectively improve the compressive strength, durability, and microstructural compactness of cement-based materials. More importantly, the C-S-H and C-(A)-S-H gels generated during cement hydration additionally contribute to environmental risk mitigation. By stably immobilizing heavy metals through physical encapsulation and chemical binding, this dual mechanism significantly mitigates leaching risks and provides a viable solution to the environmental hazards posed by gold tailings.

Building on these properties, gold tailings also show considerable potential for ultra-high-performance concrete (UHPC). Zaid et al. [94] confirmed that a 15% cement replacement with gold tailings powder enhances the 90-day compressive strength by 12.49%. Wang et al. [95] advanced this approach by simultaneously incorporating both gold tailings powder and gold tailings sand into UHPC. This innovative dual-substitution strategy resulted in an approximately 25% reduction in GWP without significantly compromising mechanical performance.

In the field of traditional construction blocks, Umar et al. [96] investigated the solidification/stabilization (S/S) of detoxified gold tailings. They found that an optimized tailings-to-cement ratio of 1:1 produces blocks that meet Grade I compressive strength standards (102.33 kg/cm^2). Furthermore, the leaching characteristics of these blocks remained well below the Toxicity Characteristic Leaching Procedure (TCLP) environmental safety limits.

Beyond their application as traditional SCMs in clinker-dependent cementitious systems, gold tailings have also been extensively investigated as precursors for clinker-free alkali-activated geopolymers. Because gold tailings often require compositional adjustment, incorporating Class F fly ash as an aluminosilicate supplement can effectively improve the geopolymerization process. For instance, Zhang et al. [97] demonstrated that the incorporation of Class F fly ash optimized the Si/Al ratio of gold tailings-based geopolymers. The effect of fly ash substitution on the mechanical performance is systematically illustrated in **Fig. 18**. As shown in the figure, the mean splitting tensile strength exhibits a pronounced increasing trend with increasing FA content. At the optimal substitution level of 15%, the splitting tensile strength reaches its maximum value, indicating a substantial improvement relative to the plain control group without FA addition. Mechanistically, this optimized formulation establishes a more favorable Si/Al balance, thereby enhancing the degree of geopolymerization and maximizing the development of splitting tensile strength. However, further increasing the FA dosage to 20% results in a slight reduction in strength, suggesting that excessive fly ash may disrupt the optimal chemical equilibrium of the system. These findings indicate that although appropriate fly ash incorporation can significantly enhance the fracture resistance of gold tailings-based geopolymers, precise control of the FA dosage remains essential. These findings highlight that while appropriate dosages of fly ash effectively improve the overall fracture performance, precisely tailoring the chemical composition is a crucial pathway for the high-value utilization of gold tailings.

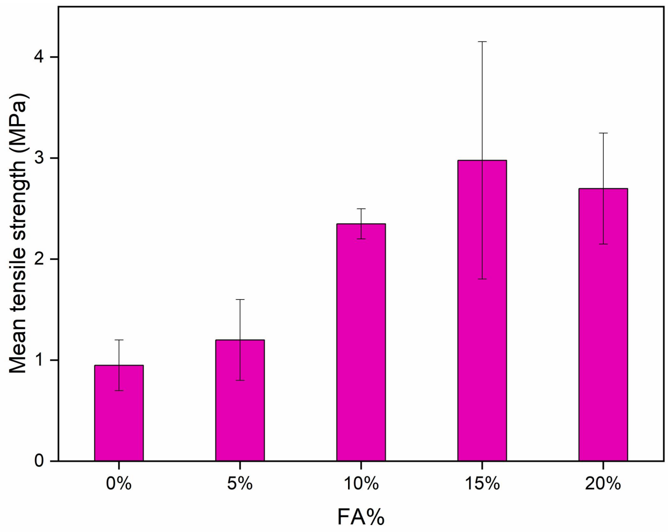


Fig. 18. Mean peak force of the Brazilian tensile test [97].

To overcome the limitations of conventional mechanical activation, recent research on copper tailings has shifted toward targeted pretreatments, such as composite activation, precise sieving, and wet grinding, aimed at simultaneously enhancing mechanical strength and specialized durability properties such as corrosion resistance. For instance, Vargas et al. [98] demonstrated the superior effectiveness of a composite activation approach that combines thermal treatment with mechanical grinding. This technique significantly enhances the cementitious reactivity of copper tailings and allows them to maintain good mechanical properties even at high replacement ratios. Subsequently, Sepulveda-Vasquez et al. [99] evaluated the effects of sieving versus grinding pretreatments. They found that incorporating 5 wt% and 10 wt% sieved copper tailings not only improved mortar strength but also substantially enhanced electrochemical stability. Microscopic analysis confirmed that these sieved tailings promote the formation of a stable oxide film on steel surfaces, which effectively retards corrosion. In UHPC applications, Tian et al. [100] explored substituting silica fume and OPC with wet-ground copper tailings. Their results showed that minor additions of wet-ground copper tailings slightly improved compressive strength while maintaining excellent chloride ion penetration resistance.

Furthermore, the feasible SCM dosage is constrained by multiple factors, including pozzolanic reactivity, clinker dilution, water demand, contaminant risks, and durability requirements. Consequently, researchers often explore concurrent fine-aggregate replacement to increase total tailings consumption. While activated tailings chemically modify the cementitious paste, replacing natural river sand with inert tailings fractions mechanically alters the aggregate skeleton. However, this application requires a delicate balance between mechanical strength and rheological stability. Zhang et al. [101] systematically evaluated the effects of this substitution. They observed that incorporating copper tailings sand inevitably reduces both workability and compressive strength to varying degrees. However, when the replacement ratio is capped at 60%, the slump decreases by only 15%, and the compressive strength drops by just 2.5%. This mixture most closely matches conventional concrete. Conversely, when the substitution rate increases to 80%, the average compressive strength falls from 37.3 MPa to 34.9 MPa, along with a 6.43% drop in the elastic modulus. This subtle degradation in mechanical robustness and the tendency toward increased brittleness are reflected in the uniaxial compressive stress-strain curves in **Fig. 19**. At low replacement levels, the curves closely mirror those of conventional concrete. However, at higher dosages, the rate of strength loss in the descending branch accelerates rapidly, and the area under the curve decreases. This indicates reduced stiffness and notably increased brittleness.

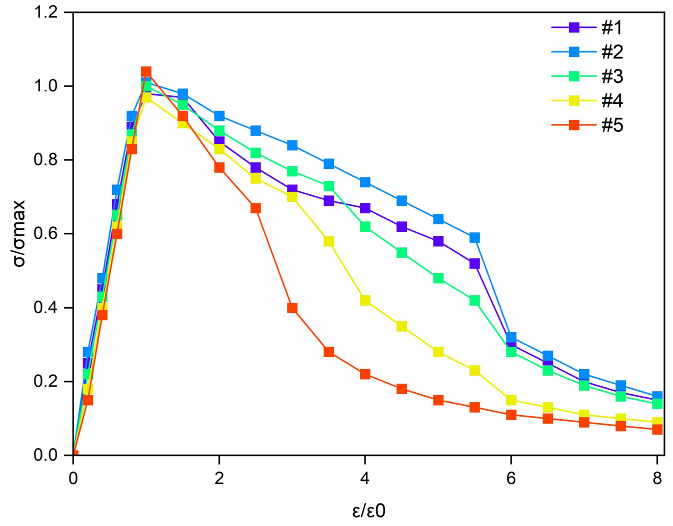


Fig. 19. Full uniaxial compressive stress-strain curves of concrete with different copper tailings sand replacement ratios [101].

Nevertheless, the long-term durability of concrete containing gold and copper tailings remains a concern due to the potential for sulfide oxidation. Therefore, tailings with high sulfur contents should be systematically evaluated through sulfide content characterization, acid-generation potential analysis, accelerated oxidation tests, sulfate-resistance assessments, and long-term leaching studies prior to their use at structural replacement levels. Metal tailings without deep desulfurization typically retain sulfide minerals such as pyrite (FeS_2) and pyrrhotite. Evidence from sulfide-bearing aggregates, such as the work of Rodrigues et al. [102], provides an important analogue for this risk, but tailings-specific validation remains necessary. When oxygen and moisture penetrate the concrete, these residual sulfides slowly oxidize to generate sulfuric acid. This in situ acid not only induces the delayed formation of secondary ettringite but also triggers extensive thaumasite precipitation, generating large internal expansive tensile stresses that ultimately lead to the cracking and disintegration of the concrete structure. Since this oxidative degradation typically takes years to manifest, relying solely on short-term strength evaluations fails to adequately capture the long-term durability risks associated with high-sulfur tailings.

Overall, selected gold and copper tailings can contribute to mechanical enhancement and heavy-metal immobilization in properly designed cementitious systems. However, this potential is strongly constrained by rheology, sulfide content, leaching behavior, and long-term durability. Nevertheless, their practical engineering application must navigate two critical thresholds. First, at extremely high dosages, water film depletion triggers a rheological crisis and macroscopic brittleness. Second, residual sulfides cause irreversible oxidative expansion damage, known as internal sulfate attack, during long-term service. Therefore, the valorization of such tailings should avoid simply pursuing high replacement ratios. It necessitates a rigorous scientific balance among rheological control, deep desulfurization treatments, and full-life-cycle durability monitoring.

5.3. Other tailings

For emerging polymetallic tailings, researchers increasingly focus on balancing macrostructural stability with environmental safety. Recent studies explore novel activation pathways designed to permanently immobilize hazardous metals, while strictly adhering to the thermodynamic thresholds of cementitious systems. As the pressure for resource recovery mounts, researchers are exploring emerging bulk solid wastes, such as nickel-cobalt, lead-zinc, red mud (bauxite residue), and tungsten-molybdenum tailings. Adesina [103] discussed the theoretical feasibility of using nickel-cobalt tailings at extreme replacement rates of up to 75%. However, in SCM mix design, researchers should impose strict constraints on such extreme dosages. For conventional OPC systems without sufficient activators or supplementary Ca/alkali sources, direct cement replacement of 70–75% is typically incompatible with normal hydration and strength gain, and the performance of alternative binder systems should be independently verified. Applying such rates directly to OPC concrete may result in severe mechanical degradation and structural instability.

Johansson et al. [104] provided rigorous benchmarks, showing that even with rigorous mechanical activation, the safe SCM replacement threshold for lead-zinc tailings must be strictly limited to 10%. Only within this stringent limit can the tailings-based binder reliably match the 28-day compressive strength of conventional OPC and prevent microstructural degradation. In exploring the SCM potential of other emerging industrial wastes, Lazorenko et al. [105] demonstrated the feasibility of utilizing tungsten–molybdenum tailings as a precursor material. Dry ball milling was employed to synergistically activate the tailings and coal bottom ash, and the effects of milling parameters on compressive strength development are illustrated in **Fig. 20**. As shown in the figure, the compressive strength of the resulting binder is highly sensitive to both rotation speed and milling duration. Compared with the unmilled control sample, which exhibited a compressive strength of only 13.6 MPa, mechanical activation markedly enhanced the reactivity of the precursor materials. The optimum performance was achieved at a rotation speed of 450 rpm (W_r = 450 rpm) and a milling time of 30 min (T_m = 30 min), resulting in a sustainable alkaline aluminosilicate binder with a peak compressive strength of 52.1 MPa. However, further increases in rotation speed (600 rpm) or milling duration (45 min) led to a slight decline in strength, indicating that excessive grinding does not necessarily translate into improved performance. These results highlight the existence of an optimal mechanochemical activation window, within which particle refinement and structural disordering are maximized without inducing adverse effects associated with over-grinding. Furthermore, Emilio and Moura [106] reviewed highly alkaline red mud and revealed a distinct SCM activation pathway. Beyond conventional aluminosilicate depolymerization, approximately 40% of the reactive iron phases in red mud can quantitatively integrate into highly stable Fe-S-H gel networks. This mechanism not only drives significant micro-morphological densification but also achieves a heavy metal immobilization efficiency exceeding 95%.

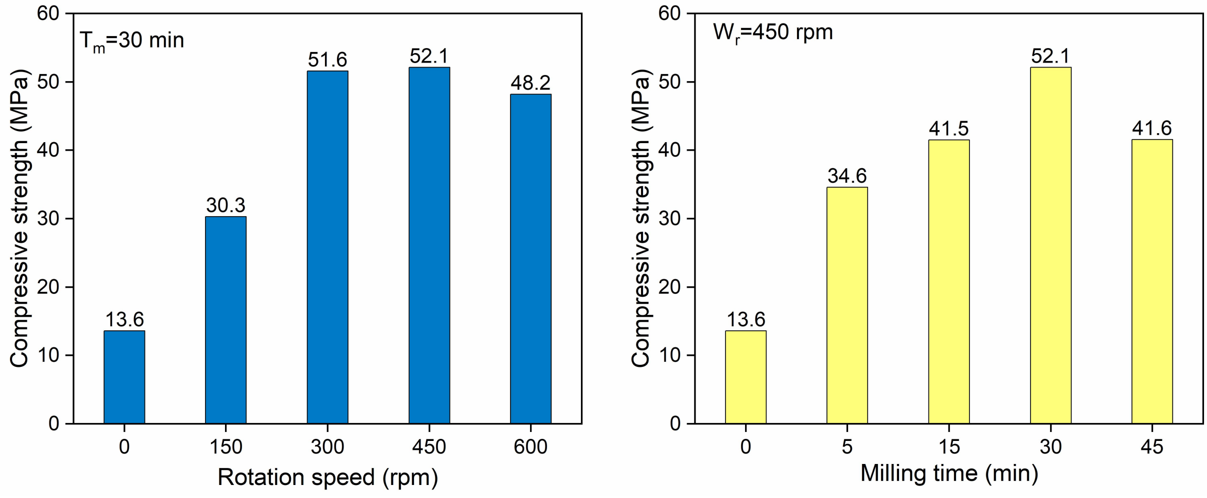


Fig. 20. Compressive strength as a function of milling rotation speed and milling duration [105].

However, it is crucial to recognize that the environmental safety of polymetallic tailings within a cementitious matrix is not static. Geotechnical consensus increasingly advocates for cemented dry stacking to prevent catastrophic physical failures, such as the 2019 Brumadinho tailings dam collapse in Brazil [107]. In that disaster, static liquefaction triggered a rapid mudflow that released approximately 10 million m^3 of iron ore tailings, killing 270 people, destroying infrastructure, and causing severe environmental contamination along the Paraopeba River. However, despite these physical stabilization efforts, solidification alone is insufficient. Even after being solidified into SCMs, these tailings remain highly sensitive to climatic weathering. Therefore, using toxic polymetallic tailings must transcend mere physical blending or encapsulation. It must actively exploit the chemical hydration networks to achieve the permanent weather-resistant immobilization of hazardous heavy metals.

6. Future perspectives and directions

6.1. Critical research gaps

The preceding sections indicate the technical potential of tailings-based SCMs while also revealing substantial uncertainties in durability, environmental safety, and life-cycle performance. Given these limitations, a systematic quantification of their full life-cycle environmental benefits remains a critical prerequisite for large-scale industrial application.

LCA provides a core methodological framework for quantifying the full-life-cycle environmental benefits of tailings-based SCMs and supporting their large-scale industrial deployment. Abiotic Depletion Potential (ADP) is a globally recognized LCA indicator for mineral resource use, incorporated into standardized frameworks by organizations such as the United Nations Environment Programme Life Cycle Initiative and the European Commission. For tailings-based SCMs, ADP should be considered together with GWP, toxicity-related metrics, water use, and long-term leaching risks to enable a comprehensive sustainability assessment [108,109]. Centered on the core concept of resource depletion, the material flow and resource loss pathways across the full mining-beneficiation chain are presented in **Fig. 21**. After mineral resources originally hosted in the crust of the Earth are transferred into human society, only a small fraction of valuable metals is enriched into concentrate products, while the vast majority of ore components enter the final stockpiling stage as tailings. This process transfers a large fraction of the ore mass into tailings storage, while subsequent weathering, dust emission, runoff, or leaching may further redistribute certain constituents into atmospheric or aquatic compartments. These secondary migration pathways ultimately drive two critical impact endpoints: resource depletion and environmental dissipation [110].

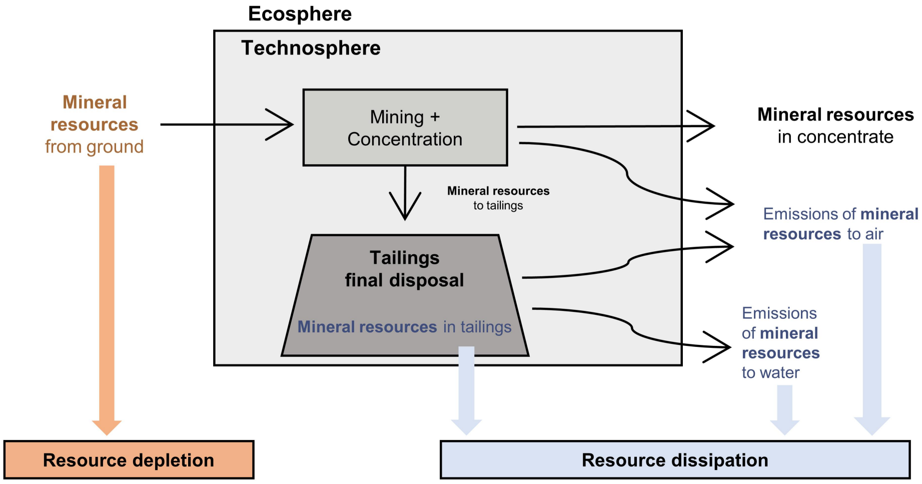


Fig. 21. Material flow of mining-beneficiation processes and ADP depletion conceptual framework [111].

In a systematic LCA review, Beylot et al. [111] reported that tailings utilization can significantly reduce disposal-related toxicity impacts, making it a more sustainable management strategy than conventional stockpiling. However, these benefits depend on the effective immobilization of hazardous constituents and the consideration of long-term weathering effects. Without these safeguards, toxicity-related impacts may be transferred across environmental compartments rather than genuinely eliminated. To capture these complex environmental interactions and prevent burden-shifting, a holistic assessment framework is indispensable. Nevertheless, the appropriate system boundary of LCA should be differentiated according to the evaluation objective. A narrow cradle-to-gate boundary is well-suited for early-stage technical screening. This approach can quickly quantify the trade-off between activation energy consumption and clinker substitution benefits, thereby enabling the efficient elimination of schemes with a net carbon increase at the preliminary stage However, this simplified boundary is insufficient to support a full sustainability assessment for industrial deployment. For instance, Delnavaz et al. [112] restricted their LCA to the manufacturing phase, tracking the process solely from extraction to the factory gate. Adiguzel et al. [113] cautioned against this practice, arguing that such limitations may severely underestimate long-term environmental risks. Short-term models often disregard the extended life cycle of concrete, which involves decades of active service prior to demolition and disposal. Consequently, these models fail to account for slow-release processes such as weathering and leaching over time, thereby systematically underestimating the long-term ecological risks of tailings-based SCMs.

To systematically quantify the environmental feasibility of tailings-based SCMs, a direct comparative LCA against conventional OPC is essential. The primary environmental impacts of OPC stem from raw limestone extraction and high-temperature clinker calcination. Clinker calcination is typically performed at 1400–1450 ℃, and generates approximately 0.8–1.0 tons of CO_2 per ton of cement produced. This process also contributes to a significant ADP. Most existing studies evaluating the environmental benefits of tailings as OPC substitutes predominantly adopt a cut-off allocation approach. Under this framework, all environmental burdens associated with initial ore extraction and primary beneficiation are fully allocated to primary metal products. As a result, raw tailings enter the LCA system boundary with no inherent upstream environmental burden [114].

Consequently, raw tailings enter the LCA system boundary without any inherent initial environmental burden. Methodologically, the carbon footprint of tailings-based SCMs stems exclusively from secondary processing operations. Examples include mechanical grinding and chemical activation. This factor confers a substantial emission reduction advantage during direct comparisons. However, relying exclusively on the cut-off approach may yield an incomplete picture. Arrigoni et al. [115] highlighted this limitation regarding the true environmental potential of SCMs. The substitution approach introduces a vital system-level perspective. It reframes tailings valorization as an active mitigation strategy. This strategy avoids the long-term management costs and ecological risks of traditional tailings impoundments. Synthesizing these two assessment perspectives is highly advantageous. It captures the direct carbon abatement benefits derived from the zero initial burden of tailings. It also quantifies the indirect systemic benefits. These indirect benefits include diverting solid waste from landfills and reducing regional resource pressure. Ultimately, this holistic analysis provides robust life-cycle evidence. This evidence supports the large-scale deployment of tailings-based low-carbon construction materials.

Furthermore, current LCA studies on solid-waste SCMs generally lack adequate uncertainty quantification, as standard matrix-based models may struggle to handle parameter variations. Chen [116] observed that researchers frequently overlook data fluctuations, even though the environmental parameters of SCMs can deviate by ±40% from default values. Additionally, substantial differences exist regarding allocation methods; for example, adopting an economic allocation method instead of a no-allocation approach can cause substantial variations in GWP results [117]. To address these inconsistencies, Gao et al. [118] proposed a three-dimensional evaluation framework that integrates resource consumption, environmental impact, and willingness-to-pay into a cohesive model. Moving forward, incorporating stochastic tools such as Monte Carlo simulations will be essential for improving evaluation accuracy.

When evaluating unconventional SCMs, relying solely on mechanical strength is inadequate. Future research should adopt multi-criteria frameworks. Nassiri et al. [119] proposed a comprehensive system integrating material availability, supply chain logistics, market readiness, technical performance, and local climate conditions. Based on this framework, the study highlighted the critical role of green procurement policies and diverse supply chains, which are essential for overcoming logistical bottlenecks. The study further underscores the imperative for interdisciplinary research, which is particularly vital for unconventional SCMs such as tailings. Researchers must systematically address inherent bottlenecks, including compositional batch variability and the lack of long-term service verification. Addressing these issues will strengthen the theoretical and technical foundation for large-scale engineering implementation.

Finally, as discussed earlier, the delayed oxidation of residual sulfides poses a severe ISA risk that short-term testing systematically fails to capture. This oxidative deterioration typically requires years of environmental exposure to manifest. Therefore, future research must move beyond reliance on conventional 28-day or 90-day laboratory evaluations. Instead, establishing standardized, multi-year field monitoring protocols is indispensable for accurately validating the long-term service life and environmental safety of these SCMs under real-world weathering conditions.

6.2. Technological innovations and integration

To overcome the extreme compositional variability of raw tailings, AI and digital twins can drive a paradigm shift from traditional trial-and-error empirical approaches to data-driven intelligent manufacturing. AI-assisted frameworks, such as those integrating machine learning with multi-objective optimization [120], explicitly map the interactions between mix components, enabling engineers to optimize cost and carbon emissions without compromising strength. AI-driven digital twins could, in principle, integrate real-time sensor data with validated prediction models, but their reliability depends on representative datasets, sensor accuracy, and plant-scale validation [121]. With validated Internet of Things (IoT) sensors and control algorithms, such systems may eventually enable near-real-time adjustment of mix proportions in response to tailings variability.

Raw tailings are characterized by pronounced compositional variability, a long-standing challenge that can be effectively addressed by AI and digital twin technologies. These technologies are driving a paradigm shift in relevant research by replacing conventional trial-and-error approaches with data-driven intelligent manufacturing paradigms. Early AI-assisted frameworks successfully integrated machine learning with multi-objective optimization to balance costs and carbon emissions. However, current frontier research demands deeper fusion with underlying physicochemical mechanisms. In the field of tailings-based SCMs, AI applications are no longer limited to simple strength prediction, and have expanded into broader research domains. The pozzolanic reactivity of tailings is jointly governed by mineral composition, particle size distribution, activation methods, and processing parameters. Traditional single-factor or orthogonal experiments show low efficiency, and often fail to yield global optimal solutions under multi-factor coupling conditions. Machine learning (ML) can construct nonlinear mapping relationships among raw material characteristics, activation parameters, and reactivity indicators using limited experimental data. This approach significantly reduces process screening costs.

The evaluation of pozzolanic reactivity for tailings-based SCMs calls for rapid and accurate testing methods. This process has long been hindered by time-consuming empirical testing protocols. To address this bottleneck, machine learning approaches are increasingly used to model complex structure-property relationships. However, a key challenge in this field is the scarcity of large-scale, high-quality experimental data. To bypass this limitation, advanced hybrid frameworks have been developed. They integrate Generative Adversarial Networks (GANs) with conventional machine learning algorithms. By synthetically augmenting limited empirical datasets, GANs create a robust training environment that enables highly accurate predictions of R^3 test reactivity metrics. These hybrid models effectively capture the non-linear relationships between a material's intrinsic physicochemical properties and its ultimate pozzolanic potential. This approach delivers a powerful data-driven tool for screening complex mineral streams.[122]. AI also plays an important role in multi-solid-waste synergistic systems, such as composite SCMs composed of tailings, steel slag, and blast furnace slag. AI can elucidate the synergistic hydration effects among different solid waste components. By quantifying the contribution weight of each component, AI overcomes the limitations of traditional empirical formulas, and supports the mix design of low-carbon cementitious materials with high solid waste content. Furthermore, in specific alkali-sulfate activation systems, the combined application of iron tailings, steel slag, and desulfurization gypsum can increase total solid waste utilization. It also enhances heavy metal immobilization performance [123].

Long-term durability evaluation presents a major challenge. Many deterioration processes progress slowly and are difficult to observe. A typical example is internal sulfate attack triggered by the oxidation of sulfides in tailings. Jiang et al. by synergizing Extreme Gradient Boosting (XGBoost) with genetic algorithm (GA), a novel optimization framework was developed to generate multidimensional contour maps for directing material design under varying sulfate exposure conditions. This data-driven approach enhanced the prediction accuracy and enabled the rapid identification of performance-optimized cement compositions, bridging laboratory research with practical engineering applications. In typical exposure scenarios, this model achieved prediction errors below 10 %, verifying its practicality and potential for engineering implementation [124].

Traditional LCA relies on static inventory data. This makes it difficult to address environmental uncertainties caused by tailings compositional fluctuations and process adjustments. Coupling ML with LCA enables rapid dynamic assessment and uncertainty analysis of environmental impacts. Ultimately, AI correlates physical performance metrics with LCA evaluation indicators, and incorporates life-cycle carbon emission and toxicity risk constraints during the mix optimization stage. This enables a tripartite forward design that integrates performance, cost and environmental performance. It avoids the unilateral pursuit of mechanical strength at the expense of long-term environmental risks.

Beyond traditional structural applications, expanding the utilization of tailings into advanced manufacturing domains, such as 3D concrete printing, introduces an entirely new dimension of high-value resource recovery, provided that their inherent rheological challenges are addressed. While tailings powder and sand are cost-effective substitutes for cement and quartz, their angularity and high internal friction can severely compromise pumpability. To mitigate these physical constraints, researchers are using secondary mixing techniques and IoT-based real-time flow monitoring. For instance, delaying the addition of superplasticizers can trigger rheological rejuvenation [125], effectively reducing static yield stress and reopening the 3D printing window for high-volume tailings concrete without sacrificing final mechanical strength.

6.3. Industrial deployment and policy implications

From an industrial deployment perspective, the techno-economic feasibility of tailings-based SCMs depends mainly on three factors: the energy cost of activation, the transportation radius, and the scale of the operation. While preliminary feasibility studies, such as the investigation by Mendez et al. [126] on gold tailings in Ecuador, support the potential use of certain tailings as aggregate substitutes in localized products, separate validation is required for their use as reactive SCMs in binder systems. There is an urgent need for systematic follow-up studies and multi-year field verification to provide the essential data required for large-scale engineering implementation. Beyond physical verification, bridging the gap between localized monitoring and long-term service reliability requires high-precision, full-life-cycle durability-prediction models, as emphasized by Zhao et al. [127], to address performance degradation under evolving climate conditions.

However, economic viability alone is insufficient to enable widespread industrial adoption. Transitioning from laboratory-scale innovations to large-scale commercialization necessitates a paradigm shift driven by robust policy frameworks, standardization, and industry-academia synergy. As highlighted by Ramirez-Van et al. [128], deep alignment between these policy frameworks and industrial practices is essential to meet the United Nations Sustainable Development Goals (SDGs) across the mining and construction sectors. To support this alignment, developing dedicated, standardized evaluation systems across the entire value chain is crucial to ensure consistent quality, clear performance benchmarks, and broader market acceptance.

Finally, beyond material production, large-scale deployment strategies should integrate resource utilization with environmental remediation. Hassan et al. [129] highlighted that current remediation efforts for toxic tailings ponds often remain disconnected from resource recovery, resulting in inadequate long-term risk management and low recovery efficiency. To overcome these hurdles, establishing a complete technical chain encompassing in-situ ecological remediation, harmless pretreatment, and high-value SCM application is essential. Consequently, governments should establish cross-ministerial collaborative incentives and regulatory mechanisms that span the mining, building materials, environmental protection, and financial sectors. Achieving this ambitious vision relies not merely on overcoming isolated technical barriers, but on fostering a holistic ecosystem where advanced material science, rigorous life-cycle assessment, and proactive policymaking converge. Ultimately, overcoming these deployment bottlenecks could substantially contribute to reducing the cement industry carbon footprint, provided that net environmental benefits and long-term safety are verified.

7. Conclusion

In summary, mine tailings are abundant and globally distributed, offering considerable potential as low-carbon SCMs. Through systematic evaluation of their chemical mechanisms, thermodynamic evolution, and life-cycle impacts, this review establishes a comprehensive framework from which the following key conclusions are drawn:

(1) Mine tailings are primarily composed of SiO_2, Al_2O_3, and Fe_2O_3, giving them a chemical composition broadly similar to traditional SCMs. However, many tailings are dominated by stable crystalline minerals and therefore exhibit limited intrinsic pozzolanic reactivity, although the amorphous phase content varies considerably among sources. Consequently, direct application is rarely effective. Rigorous mineralogical characterization and targeted activation are essential prerequisites to unlock their latent cementitious potential and prevent long-term structural issues.

(2) Activation strategies enhance the latent cementitious potential of tailings through distinct mechanisms. Mechanical and thermal methods primarily function by dismantling the long-range crystalline order and increasing the content of reactive amorphous phases. In

contrast, chemical activation relies on targeted reagents to accelerate the dissolution of inert phases, release active species, and regulate the highly reactive environment for subsequent repolymerization. Multi-field coupled activation, such as combining mechanical and thermal methods, is particularly effective in driving these physical and chemical transformations. Given the energy demands of these processes, priority for future implementation should be given to low-energy activation strategies. To evaluate these strategies, an early-stage technical screening using a simplified cradle-to-gate LCA and sensitivity analysis is recommended. This approach rapidly balances the energy penalty of activation against the carbon benefits of clinker substitution, eliminating approaches that introduce a net environmental burden. However, for a comprehensive sustainability assessment prior to large-scale industrial deployment, the system boundary must extend beyond the factory gate to encompass the full in-service life, long-term weathering, leaching risks, and end-of-life disposal. This extended scope is essential to avoid a systematic underestimation of long-term ecological impacts.

(3) The incorporation of tailings fundamentally alters the time-dependent behavior of cementitious matrices. In the early stages, physical micro-filling and heterogeneous nucleation partially compensate for the low initial reactivity of the tailings. At later stages, secondary pozzolanic reactions dominate, producing dense, foil-like C-(A)-S-H gels with a low Ca/Si ratio. Moderate replacement levels often help balance filler benefits against clinker dilution, while rheological deterioration should be controlled through particle grading, pre-wetting, admixture optimization, or surface modification. Addressing these rheological constraints is especially critical for advanced applications like 3D concrete printing, where precise control is required to maintain pumpability and buildability.

(4) Given the high variability of tailings from different sources, a universal approach is unsuitable. Iron ore tailings, for instance, are abundant but highly inert, which necessitates strong mechanochemical activation or integration into multi-solid-waste hydration networks, such as LC_3 or alkali-sulfate systems. Such multi-source systems effectively increase the total solid-waste content and, within specific formulations, enhance heavy-metal immobilization. However, these specific achievements are highly system-dependent and do not universally translate to cement replacement levels exceeding 50%. Furthermore, while certain copper and gold tailings show promising pozzolanic or filler potential after proper characterization and activation, their practical use remains constrained by risks of sulfide oxidation, heavy-metal leaching, and rheological deterioration.

(5) The utilization of mine tailings as SCMs has the potential to drive cement-industry decarbonization while alleviating the environmental burdens of tailings storage. While CO_2 emissions can be substantially reduced in specific scenarios, the net magnitude of this benefit is highly contingent on factors such as replacement levels, transport distances, and

the aforementioned activation energy demands. In contrast to the preliminary screening of activation methods, comprehensive sustainability evaluations require a broader scope. Importantly, short-term environmental indicators and cradle-to-gate screening alone are insufficient to validate overall sustainability. Comprehensive evaluations for industrial deployment must therefore employ service-life-extended cradle-to-grave LCA to account for long-term weathering effects and structural performance. Furthermore, the enduring immobilization of potentially toxic elements should be rigorously verified through empirical durability and leaching tests, rather than inferred solely from LCA models.

(6) Several critical constraints still hinder large-scale industrialization. Specifically, tailings compositions vary substantially between batches, and fresh concrete experiences severe rheological degradation. To overcome these interconnected bottlenecks, researchers should move beyond traditional trial-and-error methods toward AI-driven mix design and digital twin technologies. By combining machine learning with multi-objective optimization, these digital tools may support dynamic prediction and optimization of water, cement, and SCM ratios, provided that representative datasets, reliable sensors, and plant-scale validation are available. This integration will provide a highly adaptive, reliable foundation for the next generation of smart, ultra-low-carbon building materials.

Ultimately, the valorization of mine tailings as SCMs can reduce the carbon footprint of the cement industry but also provides a viable solution to the severe waste management challenges faced by the mining sector. This approach aligns closely with global sustainability objectives and could become a standard component of greener construction practices. However, to facilitate the widespread industrial adoption of tailings-based SCMs, the establishment of updated regulatory frameworks and standardized technical specifications is imperative to ensure safe usage and build long-term market confidence in these alternative materials.

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Author contribution statement

Leyu Hu: Writing – original draft. Zhijie Pi: Data curation, Writing – review & editing. Nan Zhang: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Validation, Writing – review & editing. Wenpeng Liu: Writing – review & editing. Junbiao He: Writing – review & editing. Peiqing Wang: Writing – review & editing. Huan Niu: Writing – review & editing.

Use of AI statement

None.

Reference

[1] Global cement CO_2 emissions 1960-2024. Statista n.d. https://www.statista.com/statistics/1299532/carbon-dioxide-emissions-worldwide-cement-manufacturing/ (accessed March 25, 2026).
[2] Snellings R, Suraneni P, Skibsted J. Future and emerging supplementary cementitious materials. Cement and Concrete Research 2023;171:107199. https://doi.org/10.1016/j.cemconres.2023.107199.
[3] Annual CO_2 emissions from cement. Our World in Data n.d. https://ourworldindata.org/grapher/annual-co2-cement (accessed May 4, 2026).
[4] Juenger MCG, Snellings R, Bernal SA. Supplementary cementitious materials: New sources, characterization, and performance insights. Cement and Concrete Research 2019;122:257–73. https://doi.org/10.1016/j.cemconres.2019.05.008.

[5] Chandran G, Ashish S, Ajayan S A, Selvaraj T. Selection criteria for mine tailings as SCM: A Comprehensive Review of Types, Properties and Performance. Minerals Engineering 2026;235:109822. https://doi.org/10.1016/j.mineng.2025.109822.
[6] Guo Y, Qu F, Li W. Advancing circular economy and construction sustainability: transforming mine tailings into high-value cementitious and alkali-activated concrete. Npj Mater Sustain 2025;3:8. https://doi.org/10.1038/s44296-025-00049-9.
[7] Gou M, Zhou L, Then NWY. Utilization of tailings in cement and concrete: A review. Science and Engineering of Composite Materials 2019;26:449–64. https://doi.org/10.1515/secm-2019-0029.
[8] Fang Y, Qiao L, Hu T, Zhang L, Long H, Yu F, et al. Characteristics of Iron Ore Tailings Sand and Properties of Iron Ore Tailings Sand Concrete: A Review. Int J Concr Struct Mater 2025;19:41. https://doi.org/10.1186/s40069-025-00784-2.
[9] Bahmani H, Mostafaei H, Wu C. Innovative Uses of Iron Ore Tailings in Sustainable Concrete: An In-Depth Review of Achievements, Future Potential, and Strategic Directions. Arab J Sci Eng 2026;51:3931–50. https://doi.org/10.1007/s13369-025-10687-9.
[10] Unlocking the Hidden Value in Global Tailings n.d. https://www.miningvisuals.com/post/from-waste-to-wealth-unlocking-the-hidden-value-in-global-tailings (accessed March 25, 2026).
[11] Lyu X, Yao G, Wang Z, Wang Q, Li L. Hydration kinetics and properties of cement blended with mechanically activated gold mine tailings. Thermochimica Acta 2020;683:178457. https://doi.org/10.1016/j.tca.2019.178457.
[12] Zhan X, Xie Z, Yue Z, Lu H, Wang J, Zhao P, et al. Optimized fabrication of iron ore tailings/lithium feldspar-based inorganic insulation boards: Insight into the formation mechanism and thermal-mechanical properties. Construction and Building Materials 2026;521:146110. https://doi.org/10.1016/j.conbuildmat.2026.146110.
[13] Mu Honglin, Li Jinyong. Experimental Study on the Influence of Gold Tailing Powder on the Mechanical Properties and Microstructure of C25 Concrete. slyjzgcxb 2024;22:189–95. (In Chinese)
[14] Kossoff D, Dubbin WE, Alfredsson M, Edwards SJ, Macklin MG, Hudson-Edwards KA. Mine tailings dams: Characteristics, failure, environmental impacts, and remediation. Applied Geochemistry 2014;51:229–45. https://doi.org/10.1016/j.apgeochem.2014.09.010.
[15] Ghazi AB, Jamshidi-Zanjani A, Nejati H. Clinkerisation of copper tailings to replace Portland cement in concrete construction. Journal of Building Engineering 2022;51:104275. https://doi.org/10.1016/j.jobe.2022.104275.

[16] Zhang S, Zhao Y, Guo Z, Ding H. Stabilization/solidification of hexavalent chromium containing tailings using low-carbon binders for cemented paste backfill. Journal of Environmental Chemical Engineering 2021;9:104738. https://doi.org/10.1016/j.jece.2020.104738.
[17] Kinnunen P, Ismailov A, Solismaa S, Sreenivasan H, Räisänen M-L, Levänen E, et al. Recycling mine tailings in chemically bonded ceramics – A review. Journal of Cleaner Production 2018;174:634–49. https://doi.org/10.1016/j.jclepro.2017.10.280.
[18] Barcelos DA, Pontes FVM, da Silva FANG, Castro DC, dos Anjos NOA, Castilhos ZC. Gold mining tailing: Environmental availability of metals and human health risk assessment. Journal of Hazardous Materials 2020;397:122721. https://doi.org/10.1016/j.jhazmat.2020.122721.
[19] Wang J, Sun X, Xing Y, Xia J, Feng X. Immobilization of mercury and arsenic in a mine tailing from a typical Carlin-type gold mining site in southwestern part of China. Journal of Cleaner Production 2019;240:118171. https://doi.org/10.1016/j.jclepro.2019.118171.
[20] Zhu Y, Wang Z, Li Z, Yu H. Experimental research on the utilization of gold mine tailings in magnesium potassium phosphate cement. Journal of Building Engineering 2022;45:103313. https://doi.org/10.1016/j.jobe.2021.103313.
[21] Li Z, Guo L, Zhao Y, Peng X, Kyegyenbai K. A Particle Size Distribution Model for Tailings in Mine Backfill. Metals 2022;12:594. https://doi.org/10.3390/met12040594.
[22] Pan Z, Xu M, Liu T, Huang J, Li X, Zhang C. Reconstruction and Microstructure Characterization of Tailings Materials with Varying Particle Sizes. Materials (Basel) 2025;18:3895. https://doi.org/10.3390/ma18163895.
[23] Reyes-Román A, Samarina T, Castillo-Godoy D, Takaluoma E, Campo G, Araya-Letelier G, et al. Use of Abandoned Copper Tailings as a Precursor to the Synthesis of Fly-Ash-Based Alkali Activated Materials. Materials 2025;18:3926. https://doi.org/10.3390/ma18173926.
[24] Wang Z, Chu H, Wang J, Feng E, Zhang Y, Lyu X. Mechanical activation of siliceous tailings and its application as cement admixtures. Minerals Engineering 2022;177:107366. https://doi.org/10.1016/j.mineng.2021.107366.
[25] Fode TA, Chande Jande YA, Kivevele T. Effects of different supplementary cementitious materials on durability and mechanical properties of cement composite – Comprehensive review. Heliyon 2023;9:e17924. https://doi.org/10.1016/j.heliyon.2023.e17924.
[26] Zhang B, Zhang Y, Liu W, Gu X, Wang Q, Zhang S, et al. Effect of Iron Tailing Powder-Based Ternary Admixture on Acid Corrosion Resistance of Concrete. Materials 2023;16:3688. https://doi.org/10.3390/ma16103688.

[27] Magalhães LF de, França S, Oliveira M dos S, Peixoto RAF, Bessa SAL, Bezerra AC da S. Iron ore tailings as a supplementary cementitious material in the production of pigmented cements. Journal of Cleaner Production 2020;274:123260. https://doi.org/10.1016/j.jclepro.2020.123260.
[28] Zhang N, Hedayat A, Han S, Ma S, Bolaños Sosa HG, Huamani Bernal RP, et al. Fracture properties of tailings-based geopolymer incorporated with class F fly ash under mode I loading conditions. Eng Fract Mech 2022;271:108646. https://doi.org/10.1016/j.engfracmech.2022.108646.
[29] Ahmed A. Assessing the effects of supplementary cementitious materials on concrete properties:a review. Discov Civ Eng 2024;1:145. https://doi.org/10.1007/s44290-024-00154-z.
[30] Simonsen AMT, Solismaa S, Hansen HK, Jensen PE. Evaluation of mine tailings' potential as supplementary cementitious materials based on chemical, mineralogical and physical characteristics. Waste Management 2020;102:710–21. https://doi.org/10.1016/j.wasman.2019.11.037.
[31] Yagüe S, Sánchez I, Vigil de la Villa R, García-Giménez R, Zapardiel A, Frías M. Coal-Mining Tailings as a Pozzolanic Material in Cements Industry. Minerals 2018;8:46. https://doi.org/10.3390/min8020046.
[32] Zeng H, Ramanathan S, Kim HJ. Effect of copper mine tailings and copper slag on the hydration, microstructure, and mechanical property in Portland cement. Results in Engineering 2025;26:104890. https://doi.org/10.1016/j.rineng.2025.104890.
[33] Kara İB, Durmuş G, Kara C, Kaplan G. Copper tailings recycling in cement-based composites: A deterministic LCA approach accompanied by microstructure, mechanical, thermal and non-destructive tests. Minerals Engineering 2026;235:109866. https://doi.org/10.1016/j.mineng.2025.109866.
[34] Arachchilage CB, Zhao J, Dushyantha N, Liu WV. A transformer-based machine learning model for optimizing the design of cementitious mixtures with mine tailings as supplementary cementitious materials. Cement and Concrete Composites 2026;165:106363. https://doi.org/10.1016/j.cemconcomp.2025.106363.
[35] Yi Longsheng, Xia Jin, Mi Hongcheng, Zhang Binghang. A review on the research progress of tailings activation methods. Journal of Mining Science and Technology. 2022;7:529–37. https://doi.org/10.19606/j.cnki.jmst.2022.05.003. (In Chinese)
[36] Fante F, Lotero A, Filho HCS, Bruschi GJ, Mafessoli M, Piovesan MA, et al. Solidification/stabilization of metallurgical tailings from the zinc process: environmental, microstructural, and mechanical aspects. Environ Sci Pollut Res 2026;33:1677–94. https://doi.org/10.1007/s11356-026-37393-9.

[37] Vigneshwari Are, Jayaprakash J. Unleash the potential of mechanically activated Iron ore tailings in cement mortar containing silica fume and fly ash. Materials Letters 2024;372:137052. https://doi.org/10.1016/j.matlet.2024.137052.
[38] Hu Z, Gu X, Liu J, Ge X, Wang S, Yin S. Mechanical properties and hydration mechanism of iron tailings–cement-based supplementary cementitious materials. Buildings 2024;14:1044. https://doi.org/10.3390/buildings14041044.
[39] Gu X, Zhang W, Zhang X, Li X, Qiu J. Hydration characteristics investigation of iron tailings blended ultra high performance concrete: The effects of mechanical activation and iron tailings content. Journal of Building Engineering 2022;45:103459. https://doi.org/10.1016/j.jobe.2021.103459.
[40] Scrivener KL, Juilland P, Monteiro PJM. Advances in understanding hydration of Portland cement. Cement and Concrete Research 2015;78:38–56. https://doi.org/10.1016/j.cemconres.2015.05.025.
[41] Lu K, Sun Q. Study on the hydration mechanism of a modified graphite tail - portland cement clinker composite cementation system. J Build Eng 2025;114:114378. https://doi.org/10.1016/j.jobe.2025.114378.
[42] Mawire G, McDonald R, Austin P, Mukherjee A, Esteban L, Dhami NK. Recycling of mine tailings as supplementary cementitious material: Impact of mine tailings' mineralogy on hydration behaviour and phase assemblage of Ordinary Portland cement blends. Cleaner Materials 2025;15:100288. https://doi.org/10.1016/j.clema.2024.100288.
[43] Geng B, Wang Z, Shi S, Wang K, Fu J, Wen Z, et al. Pozzolanic Reactivity and Hydration Products of Cementitious Material Prepared Using Molybdenum Tailings. Processes 2023;11:1101. https://doi.org/10.3390/pr11041101.
[44] Johansson L, Bahrami A, Wallhagen M, Cehlin M. A comprehensive review on properties of tailings-based low-carbon concrete: Mechanical, environmental, and toxicological performances. Developments in the Built Environment 2024;18:100428. https://doi.org/10.1016/j.dibe.2024.100428.
[45] Chen B, Pang L, Zhao Y, Fu P, Chang Q, Sun L. Effect of Activated Gold Tailings Replacing Fly Ash on the Properties of Cement-Based Grouting Material. J Mater Civ Eng 2022;34:04022066. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004209.
[46] Tan Qin. Influence of activated gold tailings dosage on mechanical properties and microstructural properties of concrete. Multipurpose Utilization of Mineral Resources. 2023;00:120. https://doi.org/10.3969/j.issn.1000-6532.2023.06.018. (In Chinese)
[47] Zhu K, Wang H, Zhao X, Luo G, Dai K, Hu Q, et al. Effects of Superfine Cement on Fluidity, Strength, and Pore Structure of Superfine Tailings Cemented Paste Backfill. Minerals 2025;15:24. https://doi.org/10.3390/min15010024.

[48] Wang Z, Chen L, Hu M. Experiment research and mechanism analysis on rheological properties of tailings slurry. Front Earth Sci 2023;10. https://doi.org/10.3389/feart.2022.1083436.
[49] Guo Z, Sun X, Zhang X, Qiu J, Jiang H, Zhao Y, et al. Effect of superplasticizer on rheology and thixotropy of superfine-tailings cemented paste backfill: Experiment and modelling. Construction and Building Materials 2022;316:125693. https://doi.org/10.1016/j.conbuildmat.2021.125693.
[50] Zhifei LIU, Xingyu FU, Du LIU, Yajun LI. Competitive adsorption of polycarboxylate superplasticizer by gangue powder and cement in backfilling engineering. gckxxb 2025;47:2388–96. https://doi.org/10.13374/j.issn2095-9389.2025.03.07.001.
[51] Deng Peng Z. Chemical-Thermal-Mechanical Complex Activation of Gold Tailings and its Mechanism Analysis. Journal of Hunan University (Natural Sciences) n.d.
[52] Wang Q, Yao G, Zhu X, Wang J, Wu P, Lyu X. Preparation of Portland Cement with Gold Ore Tailings. Advances in Materials Science and Engineering 2019;2019:1324065. https://doi.org/10.1155/2019/1324065.
[53] Figueiredo AS, Bezerra AC da S, Costa LCB, Resende DM, Kuster LD, Peixoto RAF. Sand Mining Tailings as Supplementary Cementitious Material. Buildings 2024;14:2408. https://doi.org/10.3390/buildings14082408.
[54] Wang Z, Wang Q, Zhao W, Xia C, Tian X, Jiang Y, et al. Influence of carlin-type gold mine tailings addition on the synthesis temperature, alkali-resistant performance, and hydration mechanism of Portland cement. Construction and Building Materials 2022;359:129458. https://doi.org/10.1016/j.conbuildmat.2022.129458.
[55] Cui L, Chen P, Wang L, Xu Y, Wang H. Reutilizing waste iron tailing powders as filler in mortar to realize cement reduction and strength enhancement. Materials 2022;15:541. https://doi.org/10.3390/ma15020541.
[56] Chen S, Yilmaz E, Xiang Z, Wang Y. Curing conditions effect on pore structure, compressive strength and elastic modulus of cementitious tailings backfills. Powder Technology 2023;422:118458. https://doi.org/10.1016/j.powtec.2023.118458.
[57] Zhang M, Chen J, Lv Y, Wang D, Ye J. Study on the expansion of concrete under attack of sulfate and sulfate–chloride ions. Construction and Building Materials 2013;39:26–32. https://doi.org/10.1016/j.conbuildmat.2012.05.003.
[58] 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. Journal of Cleaner Production 2019;217:12–21. https://doi.org/10.1016/j.jclepro.2019.01.175.
[59] Li W, Zheng C, Liu C, Zhang Z, Wang Z, Wang Q. Study on the performance of cement stabilized limestone tailings blending macadam in pavement base. Front Mater 2025;12. https://doi.org/10.3389/fmats.2025.1632505.

[60] Martins NP, Helser J, Plötze M, Snellings R, Habert G. Effect of sulfidic mine tailings used as mineral admixtures on the hydration of common and alternative cements. Mater Struct 2024;57:19. https://doi.org/10.1617/s11527-023-02289-4.
[61] Chen B, Pang L, Zhou Z, Chang Q, Fu P. Study on the activation mechanism and hydration properties of gold tailings activated by mechanical-chemical-thermal coupling. J Build Eng 2022;48:104014. https://doi.org/10.1016/j.jobe.2022.104014.
[62] Saedi A, Jamshidi-Zanjani A, Darban AK. A review on different methods of activating tailings to improve their cementitious property as cemented paste and reusability. Journal of Environmental Management 2020;270:110881. https://doi.org/10.1016/j.jenvman.2020.110881.
[63] Feng W, Yu Z, Bao R, Xiong J, Yan K, Liu R, et al. Manufacture of tailings-based cementitious materials: Insights into tailings activation strategies. Construction and Building Materials 2024;439:137194. https://doi.org/10.1016/j.conbuildmat.2024.137194.
[64] Wang X, Chen W, Xu J, Wang P, Hu H, Wu Y, et al. Preparation of vanadium tailings-fly ash alkali-activated materials via mechanical activation: Geopolymerization and heavy metal immobilization behavior. Results in Engineering 2026;29:109233. https://doi.org/10.1016/j.rineng.2026.109233.
[65] Cao J, Zhang Q, Wang S, Zhao Y, Cui W, Li J. High-temperature thermal activation of gold tailings: microstructure reconstruction and pozzolanic activity enhancement. Journal of Building Engineering 2026;123:115862. https://doi.org/10.1016/j.jobe.2026.115862.
[66] Zhao S, Zheng K, Liao D, Peng L, Ni L, Zhang L, et al. Activation of iron tailings with a composite activator of NaOH and CaSO4·2H2O and its effect on the strength of iron tailings-based mortar specimens. Powder Technology 2026;467:121564. https://doi.org/10.1016/j.powtec.2025.121564.
[67] Wang Z, Han H, Sun W, Wang C, Sang M. Mechanical activation and cementitious valorization of garnet tailings: lattice distortion characteristics and pozzolanic activity. Minerals Engineering 2026;235:109819. https://doi.org/10.1016/j.mineng.2025.109819.
[68] Xu R, Kong F, Tong H, Zhang Z, Liu W. Performance enhancement of copper tailings-based autoclaved aerated concrete through chemical activation: From macro-properties to microstructure evolution. Construction and Building Materials 2025;500:144216. https://doi.org/10.1016/j.conbuildmat.2025.144216.
[69] Zheng Z, Tan H, He X, Su Y, Wang Y, Yang J, et al. Physical-chemical characterization and application research of copper tailings with wet-grinding activation for use as supplementary cementitious material. Construction and Building Materials 2025;489:142077. https://doi.org/10.1016/j.conbuildmat.2025.142077.
[70] Different Effects of Wet and Dry Grinding on the Activation of Iron Ore Tailings. Journal of Renewable Materials 2021;9:2261–76. https://doi.org/10.32604/jrm.2021.015793.

[71] Hernández-Ramos SM, Trejo-Arroyo DL, Cholico-González DF, Rodríguez-Torres GM, Zárate-Medina J, Vega-Azamar RE, et al. Characterization and effect of mechanical and thermal activation in mining tailings for use as supplementary cementitious material. Case Studies in Construction Materials 2024;20:e02770. https://doi.org/10.1016/j.cscm.2023.e02770.

[72] Zhou L, Gou M, Hou W, Zhao M, Zhao J, Shen Z. Effect of thermal activation and particle size on cementitious activity of bauxite tailings. Environ Sci Pollut Res 2022;29:78960–72. https://doi.org/10.1007/s11356-022-21409-1.

[73] Vargas F, Lopez M. Development of a new supplementary cementitious material from the activation of copper tailings: Mechanical performance and analysis of factors. Journal of Cleaner Production 2018;182:427–36. https://doi.org/10.1016/j.jclepro.2018.01.223.

[74] Lin H, Yin Z, Li S. Optimization of cementitious material with thermal-activated lead–zinc tailings based on response surface methodology. Materials 2024;17:2926. https://doi.org/10.3390/ma17122926.

[75] Lemma R, Castellano CC, Bonavetti VL, Trezza MA, Rahhal VF, Irassar EF. Thermal Transformation of Illitic-Chlorite Clay and Its Pozzolanic Activity. In: Martirena F, Favier A, Scrivener K, editors. Calcined Clays for Sustainable Concrete, Dordrecht: Springer Netherlands; 2018, p. 266–72. https://doi.org/10.1007/978-94-024-1207-9_43.

[76] Lei S, Gao H, Feng R, Dai H, Bernardo E, Zhang H, et al. Effect of calcination temperature on the activity of basalt tailings for the lightweight geopolymer from microwave curing. Materials Chemistry and Physics 2024;328:129991. https://doi.org/10.1016/j.matchemphys.2024.129991.

[77] Liu Dong, Cui Xiaowei, Di Yanqing, Li Feng. Preparation of Vanadium Tailings Based Geopolymer by Mechano-alkali Activation. Conservation and Utilization of Mineral Resources. 10.13779/j.cnki.issn1001-0076.2025.08.014. (In Chinese)

[78] Wei J, Yu X, Gao W, Yang Z, Li X, Zhang H. High-performance autoclaved aerated concrete fabricated by alkali-activated low-silica molybdenum tailings. Construction and Building Materials 2025;484:141869. https://doi.org/10.1016/j.conbuildmat.2025.141869.

[79] Zhang Y, Liu B, Gu X, Nehdi ML, Zhang LV. Mechanochemical activation of iron ore tailing-based ternary supplementary cementitious materials. Construction and Building Materials 2022;346:128420. https://doi.org/10.1016/j.conbuildmat.2022.128420.

[80] Yang Y, Yang Z, Cheng Z, Zhang H. Effects of wet grinding combined with chemical activation on the activity of iron tailings powder. Case Studies in Construction Materials 2022;17:e01385. https://doi.org/10.1016/j.cscm.2022.e01385.

[81] Hu Z, Gu X, Cheng B, Wang Q, Liu J, Ge X, et al. The role of chemical activation in strengthening iron ore tailings supplementary cementitious materials. Buildings 2024;14:963. https://doi.org/10.3390/buildings14040963.

[82] Chen J, Sun Q, Li M, Dou K, Song Y, Tan X. Research on the Thermal–Mechanical Synergistic Activation Mechanism of Coal Gangue and Its Hydration Characteristics. Buildings 2026;16:152. https://doi.org/10.3390/buildings16010152.

[83] LI Chunhu, YI Yuanrong, LIU We, et al. Study on the hydration and gelling properties of copper tailings activated by thermal-mechanical synergy LI]China Mining Magazine, 2024, 33(2): 149-158. (In Chinese)

[84] 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. Construction and Building Materials 2025;463:140109. https://doi.org/10.1016/j.conbuildmat.2025.140109.

[85] Amjad H, Abd-Elaal E-S, Ma X, Benn T, Fisher M. A critical review of iron ore tailings as cement and aggregate substitutes for robust infrastructure: mechanical, durability, eco-economic, and social impacts. Journal of Cleaner Production 2025;492:144853. https://doi.org/10.1016/j.jclepro.2025.144853.

[86] Yao G, Wang Q, Wang Z, Wang J, Lyu X. Activation of hydration properties of iron ore tailings and their application as supplementary cementitious materials in cement. Powder Technology 2020;360:863–71. https://doi.org/10.1016/j.powtec.2019.11.002.

[87] Li H, Liu F, Zhen H, Xiong Z, Song Y, Wang J, et al. Evaluating strength, hydration characteristics, microstructure evolution, and sustainability of seawater–sea sand cement-based materials containing iron ore tailings. Construction and Building Materials 2024;457:139163. https://doi.org/10.1016/j.conbuildmat.2024.139163.

[88] Goulart Bezerra C, Abelha Rocha CA, Siqueira IS de, Toledo Filho RD. Feasibility of iron-rich ore tailing as supplementary cementitious material in cement pastes. Construction and Building Materials 2021;303:124496. https://doi.org/10.1016/j.conbuildmat.2021.124496.

[89] Wang H, Gu X, Xu X, Liu J, Zhu Z, Wang S. The effects of iron tailings on steel slag-based cementitious systems: Strength, hydration products, and volume stability. Journal of Building Engineering 2024;91:109702. https://doi.org/10.1016/j.jobe.2024.109702.

[90] Zhang Y, Zhang L, Wang Q, Han D, Li Z. Iron ore tailings, phosphate slags, and lithium slags as ternary supplementary cementitious materials for concrete: Study on compression strength and microstructure. Materials Today Communications 2023;36:106644. https://doi.org/10.1016/j.mtcomm.2023.106644.

[91] Zhang B, Muhammad F, Yu T, Fahimizadeh M, Hassan MAS, Liang J, et al. Harnessing iron tailings as supplementary cementitious materials in Limestone Calcined Clay Cement (LC3): An innovative approach towards sustainable construction. Construction

and Building Materials 2024;453:139111. https://doi.org/10.1016/j.conbuildmat.2024.139111.
[92] Khamseh B, Shourijeh PT, Binesh SM. Strength and deformation characteristics of cement-stabilized Fe-rich fine iron ore tailings. Construction and Building Materials 2025;463:140101. https://doi.org/10.1016/j.conbuildmat.2025.140101.
[93] Maali A, Bediwy A, Mohamedelhassan E. Gold mine tailings in concrete and SCMs: Comprehensive review of reactivity enhancement, optimized performance, and pathways to sustainability. Materials Today Advances 2026;29:100688. https://doi.org/10.1016/j.mtadv.2026.100688.
[94] Zaid O, Ahmed M, Yosri AM, Alshammari TO. Evaluating the impact of mine tailings wastes on the development of sustainable Ultra High Performance Fiber Reinforced concrete. Sci Rep 2025;15:6285. https://doi.org/10.1038/s41598-025-88683-0.
[95] Wang JN, Yu R, Xu WY, Hu CY, Shui ZH, Qian D, et al. A novel design of low carbon footprint Ultra-High Performance Concrete (UHPC) based on full scale recycling of gold tailings. Construction and Building Materials 2021;304:124664. https://doi.org/10.1016/j.conbuildmat.2021.124664.
[96] Umar YP, Weys E, Anugroho F, Setiani P, Tri CL. Sustainable utilization of gold mining tailings in concrete block production through solidification techniques. J Ecol Eng 2026;27:176–89. https://doi.org/10.12911/22998993/209618.
[97] Zhang N, Hedayat A, Bolaños Sosa HG, Huamani Bernal RP, Tupa N, Yanqui Morales I, et al. On the incorporation of class F fly-ash to enhance the geopolymerization effects and splitting tensile strength of the gold mine tailings-based geopolymer. Construction and Building Materials 2021;308:125112. https://doi.org/10.1016/j.conbuildmat.2021.125112.
[98] Vargas F, Lopez M, Rigamonti L. Environmental impacts evaluation of treated copper tailings as supplementary cementitious materials. Resources, Conservation and Recycling 2020;160:104890. https://doi.org/10.1016/j.resconrec.2020.104890.
[99] Sepúlveda-Vásquez C, Carrasco-Astudillo N, Muñoz L, Molina P, Ringuedé A, Guerra C, et al. Electrochemical analysis of carbon steel embedded in mortars with pretreated copper tailings as supplementary cementitious material. International Journal of Electrochemical Science 2024;19:100584. https://doi.org/10.1016/j.ijoes.2024.100584.
[100] Tian B, Wang N, Ye R, Li X, Zhang B. The utilization of wet grinding copper tailing for preparing ultra-high performance concrete. Next Materials 2025;9:101085. https://doi.org/10.1016/j.nxmate.2025.101085.
[101] Zhang Z, Gao N, Wang H. The Effect of Copper Tailings Sand on the Workability and Mechanical Properties of Concrete. Buildings 2024;14:1789. https://doi.org/10.3390/buildings14061789.

[102] Rodrigues A, Duchesne J, Fournier B, Durand B, Rivard P, Shehata M. Mineralogical and chemical assessment of concrete damaged by the oxidation of sulfide-bearing aggregates: Importance of thaumasite formation on reaction mechanisms. Cement and Concrete Research 2012;42:1336–47. https://doi.org/10.1016/j.cemconres.2012.06.008.

[103] Adesina A. Characterization of mine tailings and utilization as partial replacement of cement. Physics and Chemistry of the Earth, Parts A/B/C 2026;143:104344. https://doi.org/10.1016/j.pce.2026.104344.

[104] Johansson L, Bahrami A, Cehlin M, Wallhagen M. Experimental Investigation on Using Lead–Zinc Tailings as Low-Carbon Partial Replacement of Cement in Mortar for Sustainable Construction. Buildings 2026;16:730. https://doi.org/10.3390/buildings16040730.

[105] Lazorenko G, Kruglikov A, Mokichev V, Kasprzhitskii A. Dry-ball-milling-assisted activation of tungsten-molybdenum tailings and coal bottom ash: Enhancing the co-utilization into sustainable alkaline aluminosilicate binders. Materials Letters 2026;409:140233. https://doi.org/10.1016/j.matlet.2026.140233.

[106] Emilio DDS, Moura JBD. Potential for waste recovery from bauxite mining: economic and sustainable alternatives. DCS 2026;23:e4707. https://doi.org/10.54899/dcs.v23i88.4707.

[107] Silva Rotta LH, Alcântara E, Park E, Negri RG, Lin YN, Bernardo N, et al. The 2019 Brumadinho tailings dam collapse: Possible cause and impacts of the worst human and environmental disaster in Brazil. International Journal of Applied Earth Observation and Geoinformation 2020;90:102119. https://doi.org/10.1016/j.jag.2020.102119.

[108] Berger M, Sonderegger T, Alvarenga R, Bach V, Cimprich A, Dewulf J, et al. Mineral resources in life cycle impact assessment: part II– recommendations on application-dependent use of existing methods and on futuremethod development needs. Int J Life Cycle Assess 2020;25:798–813. https://doi.org/10.1007/s11367-020-01737-5.

[109] Zampori L, Pant R. Suggestions for updating the Product Environmental Footprint (PEF) method. JRC Publications Repository 2019. https://doi.org/10.2760/424613.

[110] De Bruijn H, Van Duin R, Huijbregts MAJ, Guinee JB, Gorree M, Heijungs R, et al., editors. Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. vol. 7. Dordrecht: Springer Netherlands; 2002. https://doi.org/10.1007/0-306-48055-7.

[111] Beylot A, Bodénan F, Guezennec A-G, Muller S. LCA as a support to more sustainable tailings management: critical review, lessons learnt and potential way forward. Resources, Conservation and Recycling 2022;183:106347. https://doi.org/10.1016/j.resconrec.2022.106347.

[112] Delnavaz M, Sahraei A, Delnavaz A, Farokhzad R, Amiri S, Bozorgmehrnia S. Production of concrete using reclaimed water from a ready-mix concrete batching plant:

Life cycle assessment (LCA), mechanical and durability properties. Journal of Building Engineering 2022;45:103560. https://doi.org/10.1016/j.jobe.2021.103560.
[113] Adiguzel D, Tuylu S, Eker H. Utilization of tailings in concrete products: A review. Construction and Building Materials 2022;360:129574. https://doi.org/10.1016/j.conbuildmat.2022.129574.
[114] Simões F, Rios-Davila F-J, Paiva H, Maljaee H, Morais M, Ferreira VM. Sustainability Evaluation Using a Life Cycle and Circular Economy Approach in Precast Concrete with Waste Incorporation. Applied Sciences 2021;11:11617. https://doi.org/10.3390/app112411617.
[115] Arrigoni A, Panesar DK, Duhamel M, Opher T, Saxe S, Posen ID, et al. Life cycle greenhouse gas emissions of concrete containing supplementary cementitious materials: cut-off vs. substitution. Journal of Cleaner Production 2020;263:121465. https://doi.org/10.1016/j.jclepro.2020.121465.
[116] Chen X. Uncertainty Estimation in Matrix-based Life Cycle Assessment Models. thesis. Carnegie Mellon University, 2018. https://doi.org/10.1184/R1/6724100.v1.
[117] Chen X, Matthews HS, Griffin WM. Uncertainty caused by life cycle impact assessment methods: Case studies in process-based LCI databases. Resources, Conservation and Recycling 2021;172:105678. https://doi.org/10.1016/j.resconrec.2021.105678.
[118] Gao S, Xu J, Huang Z, Nishiwaki T, Rong C. Life Cycle Environmental Evaluation Framework for Mining Waste Concrete: Insights from Molybdenum Tailings Concrete in China. Buildings 2025;15:3755. https://doi.org/10.3390/buildings15203755.
[119] Nassiri S, Butt AA, Zarei A, Roy S, Filani I, Pandit GA, et al. Opportunities for Supplementary Cementitious Materials from Natural Sources and Industrial Byproducts: Literature Insights and Supply Assessment. Buildings 2025;15:3099. https://doi.org/10.3390/buildings15173099.
[120] Zhang Y, Peng J, Wang Z, Xi M, Liu J, Xu L. Machine Learning-Assisted Sustainable Mix Design of Waste Glass Powder Concrete with Strength–Cost–CO2 Emissions Trade-Offs. Buildings 2025;15:2640. https://doi.org/10.3390/buildings15152640.
[121] Ebad SA, Abueid AI, Amara M, Ahmed R. AI-Driven Digital Twins in Mining Operations: A Comprehensive Review. Technologies 2026;14:269. https://doi.org/10.3390/technologies14050269.
[122] Jeon D, Han S, Jung S, Moon J. Hybrid machine learning framework for predicting pozzolanic reactivity: Integration of R3 test and GAN-augmented data. Construction and Building Materials 2025;485:141959. https://doi.org/10.1016/j.conbuildmat.2025.141959.

[123] Hao J, Fang K, Zhou Z, Zhuang S. Advances in steel slag modification and synergistic mechanisms via multi-source solid waste integration for performance enhancement. ZKG 2026;2026. https://doi.org/10.32604/zkg.2026.074665.

[124] Jiang C, Chen G, Li S, Gong J, Mu Z, Xie G. Machine learning-aided prediction and genetic algorithm optimization of sulfate resistance in Portland cement-based materials. Construction and Building Materials 2025;494:143334. https://doi.org/10.1016/j.conbuildmat.2025.143334.

[125] Zhu W, Liu C, Zhang Y, Zhu C, Wang T, Wang Y, et al. Rheological rejuvenation and structural build-up of 3D printed manufactured sand concrete via secondary mixing protocol. Journal of Building Design and Environment 2026;4:2025141–2025141. https://doi.org/10.70401/jbde.2026.0029.

[126] Méndez D, Guzmán-Martínez F, Acosta M, Collahuazo L, Ibarra D, Lalangui L, et al. Use of Tailings as a Substitute for Sand in Concrete Blocks Production: Gravimetric Mining Wastes as a Case Study. Sustainability 2022;14:16285. https://doi.org/10.3390/su142316285.

[127] 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. Journal of Cleaner Production 2025;518:145933. https://doi.org/10.1016/j.jclepro.2025.145933.

[128] Ramírez-Van stralhen JJ, Romero-Perdomo F, González-Curbelo MÁ. Investigating the mining sector’s alignment with the Sustainable Development Goals in South America. Miner Econ 2026. https://doi.org/10.1007/s13563-025-00597-5.

[129] Hassan S, Bhadwal SS, Khan M, Sabreena, Nissa K-U, Shah RA, et al. Revitalizing contaminated lands: A state-of-the-art review on the remediation of mine-tailings using phytoremediation and genomic approaches. Chemosphere 2024;356:141889. https://doi.org/10.1016/j.chemosphere.2024.141889.

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