

Exploring the Potential for Utilization of Medium and Highly Sulfidic Mine Tailings in Construction Materials: a Review

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Table S-1. Highlights of publications on the effect of minor elements in ye'elimite containing cements.

Ref.	Type of cement used	Effect on	Method	Trace elements	Effects observed
[1]	pure ye'elimite, without gypsum and with 20% gypsum addition	Hydration	dissolution of metal salts (Pb(NO ₃) ₂ , Cr(NO ₃) ₃ ·9H ₂ O, Cu(NO ₃) ₂ ·3H ₂ O, Zn(NO ₃) ₂ ·6H ₂ O) in mixing water at a concentration of 0.1 or 0.5 mol L ⁻¹	Pb	In the samples of pure C4A3S, strong hydration retardation was observed; in the samples containing gypsum, hydration acceleration was observed; modification of hydration mechanism (ettringite formed instead of Afm and AH3)
				Cr	acceleration of hydration, especially in the pure C4A3S samples; modification of hydration mechanism (ettringite formed instead of Afm and AH3)
				Cu	pure C4A3S: strong impact on early hydration; acceleration but much lower hydration degree, reduced ettringite formation. Lower heat release and mass loss in the sample containing gypsum. Modification of hydration mechanism (ettringite formed instead of Afm and AH3)
				Zn	pure C4A3S: acceleration. C4A3S + gypsum: slight retardation. Impact is less significant than other heavy metals on both systems
[2]	CSA clinker + 20 or 30% phosphogypsum	hydration, immobilization	Cr added at 65 g/kg as Na ₂ CrO ₄ ·4H ₂ O (Cr ⁶⁺) and Cr(NO ₃) ₃ ·9H ₂ O (Cr ³⁺)	Cr 6+	immobilization is higher at 20% gypsum
				Cr3+	efficient immobilization regardless of gypsum content
[3]	synthetic CSA clinker and pure synthetic ye'elimite	immobilization	Pb added at PbO ₂ (0-33.71 wt%) to the raw meal	Pb	Ye'elimite XRD peaks continuously shifted to the left as Pb addition increases; simulations suggest the preferential substitution of Pb in Ca sites in ye'elimite, rather than ferrite or belite
[4]	synthetic alite-belite-ye'elimite clinker + 14% anhydrite	mineralogy, hydration	CaF ₂ , B ₂ O ₃ , Na ₂ O, and K ₂ O (1-2wt%) added to the clinker raw meal as ZnSO ₄ ·H ₂ O, Na ₂ B ₄ O ₇ ·10H ₂ O, K ₂ CO ₃ and Na ₂ CO ₃	F, Zn	1 wt% of CaF ₂ and 1 wt% of ZnO enables the coexistence of alite and ye'elimite; higher 1-day compressive strength
				F, Zn, B, Na	0.6 wt% of B ₂ O ₃ and 0.3 wt% of Na ₂ O enables stabilization of α'H polymorph of belite; additional borax has not contributed to stabilization; much higher 28-days compressive strength; Zn and F are mainly incorporated into ferrite and alite
[5]	commercial CSA clinker + 20% gypsum	Immobilization, hydration, microstructure	dissolution of 0.5 mol/L of ZnCl ₂ in mixing water	Zn	No detection of Zn in the leachate; at early age (<1 day) Zn immobilized by the precipitation of an unknown phase (possibly LDH); at later age, the most probable mechanism was sorption of Zn ²⁺ onto aluminum hydroxide
[6]	synthetic BYF clinker + anhydrite (95:5 mass ratio)	clinker mineralogy, cement hydration, and	B, Na, and Ba added to the clinker raw meal as H ₃ BO ₃ , Na ₂ CO ₃ ,	B	stabilization α'H polymorph of belite; increase in proportion of cubic ye'elimite; increase in cumulative heat
				B/Na	stabilization α'H polymorph of belite; increase in proportion of cubic ye'elimite; incorporation of Na into belite and ye'elimite; decrease in cumulative heat at 3 days; decrease in degree of hydration of ye'elimite

		compressive strength	and BaCO ₃ (0.06-0.2mol/mol belite)	B/Ba	stabilization α' H polymorph of belite; increase in proportion of cubic ye'elimite; incorporation of Ba into belite and ye'elimite; increase in cumulative heat at 3 days; increase in degree of hydration of ye'elimite; formation of barite circles around clinker particles
[7]	mixture of synthetic ye'elimite, gypsum, and lime in stoichiometric ratios for ettringite formation	Immobilization, crystal morphology	dissolution of 10%(of binder) metal salts Cd(NO ₃) ₂ , Cr(NO ₃) ₃ , Cu(NO ₃) ₂ , Fe(NO ₃) ₃ , Mn(NO ₃) ₃ , Ni(NO ₃) ₂ , Pb(NO ₃) ₂ , Zn(NO ₃) ₂ , K ₂ CrO ₄ and K ₂ MoO ₄ in mixing water	Cd	excellent stabilization in water and pH 4 HNO ₃ ; >80% metal release in pH 4.74 acetic acid/sodium acetate buffer
				Cr ³⁺	excellent stabilization in water and pH 4 HNO ₃ ; >35% metal release in pH 4.74 acetic acid/sodium acetate buffer
				Cu	excellent stabilization in water and pH 4 HNO ₃ ; >35% metal release in pH 4.74 acetic acid/sodium acetate buffer
				Fe ³⁺	excellent stabilization in water and pH 4 HNO ₃ ; >35% metal release, lower integrity loss, and needle-like ettringite microcrystals in pH 4.74 acetic acid/sodium acetate buffer
				Mn	excellent stabilization in water and pH 4 HNO ₃ ; <10% metal release in pH 4.74 acetic acid/sodium acetate buffer
				Ni	excellent stabilization in water and pH 4 HNO ₃ ; >10% metal release in pH 4.74 acetic acid/sodium acetate buffer
				Pb	Loss of physical integrity and higher leached quantities in water and pH 4 HNO ₃ ; >10% metal release, high integrity loss and no well-defined microcrystals in pH 4.74 acetic acid/sodium acetate buffer
				Zn	excellent stabilization in water and pH 4 HNO ₃ ; >35% metal release, lower integrity loss and needle-like ettringite microcrystals in pH 4.74 acetic acid/sodium acetate buffer
				(CrO ₄) ²⁻	Loss of physical integrity and higher leached quantities in water and pH 4 HNO ₃ ; >10% metal release in pH 4.74 acetic acid/sodium acetate buffer
				(MoO ₄) ²⁻	Loss of physical integrity and higher leached quantities in water and pH 4 HNO ₃ ; >10% metal release, high integrity loss and no well-defined microcrystals in pH 4.74 acetic acid/sodium acetate buffer
[8]	CSA clinker + 20 or 30% phosphogypsum	Immobilization, hydration, crystal morphology	dissolution of metal salts Na ₂ CrO ₄ I ₄ H ₂ O((CrO ₄) ²⁻); Na ₂ Cr ₂ O ₇ I ₂ H ₂ O((Cr ₂ O ₇) ²⁻); CrCl ₃ I ₆ H ₂ O(Cr ³⁺); Pb(NO ₃) ₂ ; Zn(NO ₃) ₂ I ₆ H ₂ O; ZnSO ₄ I ₇ H ₂ O; and CdCl ₂ I ₅ H ₂ O in mixing water at a concentration of 0.069mol/kg of binder	(CrO ₄) ²⁻	Loss of physical integrity; higher percent of macropores; apparent delay in ettringite precipitation (conductivity and solution analysis); much higher leached quantities, especially at 30% gypsum; numerous short hexagonal crystals of ettringite
				(Cr ₂ O ₇) ²⁻	Loss of physical integrity; higher percent of macropores; apparent delay in ettringite precipitation (solution analysis); higher leached quantities, especially at 30% gypsum; numerous short hexagonal crystals of ettringite
				Cr ³⁺	acceleration in ettringite precipitation (solution analysis), excellent stabilization regardless of gypsum %; hollow and more elongated ettringite crystals
				Pb	excellent stabilization regardless of gypsum %
				Zn	excellent stabilization regardless of gypsum %
				Cd	excellent stabilization regardless of gypsum %
[9]	Commercial CSA clinker and CSA cement	Hydration	0.5M of B added as boric acid in mixing water + NaOH to reach pH 7	B	No crystalline products observed up to 28 days; no heat released for 72h. Dense amorphous layer of ulexite covering CSA clinker particles retards hydration; crystalline ulexite detected at 56 days.

[10]	ye'elimite phase (purity was not reported) with and without SrSO ₄ and gypsum	Hydration	SR and Ba added as SrSO ₄ or BaSO ₄ in stoichiometric molar ratios to form C ₃ A ₃ SrSO ₄ and C ₃ A ₃ BaSO ₄	Sr	Hydration of Sr-doped ye'elimite + gypsum produced ettringite and AH ₃ ; SrSO ₄ detected; poorly connected microstructure; lath-like ettringite; gypsum lowers compressive strength. Hydration of Sr-doped ye'elimite + SrSO ₄ produced Afm, AH ₃ , CAH ₁₀ and less ettringite; more SrSO ₄ detected; denser microstructure; SrSO ₄ higher compressive strength, but strength loss at 90 days.
				Ba	Reaction delayed by gypsum. Hydration of Ba-doped ye'elimite + gypsum produced ettringite, monosulfate and AH ₃ ; BaSO ₄ detected; poorly connected microstructure; lath-like ettringite; gypsum lowers compressive strength.
[11]	Pure C ₄ AF clinker	Hydration, Mineralogy	Samples were prepared with dosages of 0.02, 0.1, 0.5, 2.5, and 5.0 wt.% of Cr, Ni, and Zn (in form of their oxides) in mixing water	Cr	In the sample with Cr, absolutely no C ₃ AH ₆ could be detected by XRD, but a small amount of C ₂ AH ₈ was found; the compound Ca ₄ Al ₆ O ₁₂ CrO ₄ was still unchanged; after 28 days only the hydration of the sample with Cr remained incomplete and much C ₄ AH ₁₃ and C ₂ AH ₈ was found; Cr delays and decreases substantially heat liberation
				Ni	After one day, the rate of hydration of the sample from pure C ₄ AF and the sample with Ni were identical; compared to pure C ₄ AF, Ni gives a higher rate of maximum heat liberation
				Zn	the rate of hydration of the sample with Zn was about 70% that of pure C ₄ AF; the effect of Zn on the heat liberation is very small
[12]	Synthesized C ₃ S and C ₄ A ₃ S	Mineralogy	Addition of CuO into raw meal. Weight % used were 0.1, 0.3, 0.5, 1	Cu	Cu can lower the formation temperature of C ₄ A ₃ S by about 50 °C; coexistence with C ₃ S is facilitated; when the addition of CuO reaches 1.0%, the amount of C ₄ A ₃ S decomposes
[13]	Industrial CSA clinker pure and +10, 20 or 35% gypsum	Hydration, Mineralogy	The mixing solution was prepared by dissolving the appropriate amount of analytical grade salt (ZnCl ₂ 0, 0.01 or 0.5 mol/L, ZnSO ₄ ·7H ₂ O 0 or 0.5 mol/L, Zn(NO ₃) ₂ ·6H ₂ O 0 or 0.5 mol/L, CaCl ₂ ·2H ₂ O 0 or 0.5 mol/L, Ca(NO ₃) ₂ ·4H ₂ O 0 or 0.5 mol/L) into distilled water	ZnCl ₂	This salt tended to retard the hydration process, especially when the binder did not contain any gypsum; when the gypsum content reached 20%, the retardation was only noticeable for a 0.5 mol/L ZnCl ₂ concentration; the strong accelerating effect of gypsum was predominant and mortars were only slightly retarded; with 20% gypsum zinc was efficiently insolubilized; the most probable mechanism would be an incorporation of Zn in the interlayer of C–S–H
				ZnSO ₄	Mortars prepared with a gypsum-free cement hydrated more rapidly when the mixing solution contained zinc cations instead of calcium cations
				Zn(NO ₃) ₂	Mortars prepared with a gypsum-free cement hydrated more rapidly when the mixing solution contained zinc cations instead of calcium cations
				CaCl ₂	Retarding effect; rapid precipitation of Friedel's salt, at the expense of ettringite and other AFm phases during the retardation period; the strong accelerating effect of gypsum was predominant and mortars were only slightly retarded
				CaSO ₄	Sample without gypsum: accelerates hydration
				Ca(NO ₃) ₂	Sample without gypsum: retards hydration but not as much as CaCl ₂
				Cr ³⁺	Especially in the case of chromium, AFt or AFm phases appeared in both samples from day 1; 5,000 ppm and 1,000 ppm Cr accelerated the hydration; 10,000 ppm Cr retarded

[14]	Industrial CSA clinker alone or +20% gypsum	Hydration	Mixing solution was either demineralized water or a solution containing 1 mol/L of borate ions at pH 11	B/Na	Borate ions retarded CSA cement hydration, mainly when gypsum content of the binder was high.; rapidly partially depleted from the mixing solution and precipitated into two hydrates: ulexite and a mixed AFt-type phase; duration of the period of low thermal activity increased with the amount of ulexite precipitated, acceleration of cement hydration occurred only when this phase was destabilized and began to dissolve; preventing, or limiting, the precipitation of ulexite was found to be an efficient way to decrease the retardation of CSA cement hydration due to borate ions. This could be achieved by decreasing the gypsum content of the cement, or by increasing the sodium content of the mixing solution.
[15]	Industrial CSA clinker alone or +10% gypsum	Hydration	Water-to-cement (w/c) ratio of 0.6 and mixed with several solutions of lithium hydroxide (0 to 0.1 mmol Li/g of cement)	Li	Acceleration of CSA hydration at 25 °C did not vary linearly with its concentration in solution; increased strongly for small additions (Li/C ratio from 0 to 0.03 mmol/g and leveled off for higher additions; the fast initial precipitation of Li-containing Al(OH)3 consumed aluminate ions from the solution, which in turn promoted the dissolution of ye'elimite and mayenite
[16]	Industrial CSA clinker	Immobilization, Setting time, Compressive strength, Microstructure	Soluble salts (Cr(NO ₃) ₃ · 9H ₂ O, Pb(NO ₃) ₂ , Cd(NO ₃) ₂ · 4H ₂ O) were dissolved in deionized water to prepare solutions with concentrations of 2 g/L, 4 g/L, 6 g/L, 8 g/L, and 10 g/L	Cr ³⁺	As the concentrations of added Cr ³⁺ increased, the leaching concentrations of Cr ³⁺ in CSA increased; retarded the setting time of CSA slightly; setting time was gradually extended with the increase of initial concentration; compressive strength changed by only a small amount; promoted the longitudinal growth of ettringite.
				Pb	Leaching concentrations were less than 5 mg/L; small effects on the setting time of CSA pastes; initial and final setting time were shortened by less than 5 min with the increase in Pb ²⁺ initial concentrations; compressive strength of was slightly higher than that without Pb ²⁺ ; ettringite crystals became a short sheet and the longitudinal length of the crystals was shortened
				Cd	Very good immobilization; clear retardation effect; when the concentrations of added Cd ²⁺ increased from 0 to 10 g/L, the setting times of CSA pastes were continuously prolonged; compressive strength increased when the concentration of added Cd ²⁺ was 2 g/L; compressive strength decreased slightly by increasing concentrations of added Cd ²⁺ ; ettringite grew to a shape of flake with a high length and the number of crystals increased significantly
[17]	Synthesized C4A3\$ clinker		Samples of ye'elimite corresponding to the formula Ca ₄ (Al _{1-x} Fe _x) ₆ SO ₁₆ (with x = 0.00, 0.02, 0.05, 0.07, 0.1, 0.12, 0.15, and 0.25) were synthesized from stoichiometric amounts of analytical reagent grade CaCO ₃ , Al(OH) ₃ , CaSO ₄ ·2H ₂ O, and Fe ₂ O ₃	Fe ³⁺	Substitution of the Fe ³⁺ ions into ye'elimite improved the stability of the cubic phase at room temperature; facilitated the transformation process from orthorhombic to cubic; early hydration kinetics were faster for the Fe ³⁺ -doped ye'elimite; after 30 hours of hydration, the values of the cumulative heat of the Fe ³⁺ -doped ye'elimite phase were almost the same as pure ye'elimite

[18]	Synthesized CSA clinker	Hydration, Compressive strength	Zinc was introduced into the raw meal as ZnO to produce doped clinkers. The amount of ZnO added was 0.1, 0.3, 0.5, 1 or 2 wt%	Zn	Threshold limit for zinc was found to be 0.3 wt% regardless of the CSA clinker composition; no major effect on cement hydration was observed; after 7 days of curing, the compressive strength of the cement paste doped with zinc was equivalent to that of the reference
[19]	Industrial CSA clinker	Hydration, Microstructure	Mixed with three different kinds of lithium compounds, Li ₂ CO ₃ , LiCl and Li ₂ SO ₄ . Amounts used were 0, 0.2%, 0.4%, 0.6% and 0.8 wt. %	Li ₂ CO ₃	Could significantly accelerate the hydration process; improved the precipitation of CaCO ₃ for denser microstructure
				LiCl	Could significantly accelerate the hydration process; might accelerate the hydration process by facilitating the transformation of AFm phase into Friedel's salt and swapping out SO ₄ ²⁻ required for the Aft formation; might cause corrosion of steel bars
				Li ₂ SO ₄	Could significantly accelerate the hydration process; might increase the content of active calcium sulfate, which further reacted with AH ₃ and CH produced by hydration to promote the growth of Aft; could promote the early strength
[20]	Synthesized C4A3\$	Hydration, Mineralogy, Microstructure	BaCO ₃ was added to the raw meal to obtain C3.5B0.5A3\$ and C3BA3\$	Ba/Ca	Reacts faster than the stoichiometric ye'elimite; releases less heat than the stoichiometric ye'elimite; hydration sequences and main products vary significantly with different Ba/Ca ratios; AFt is absent for the system with barium incorporation in the selected curing ages and AFm tends to be less with the increase of Ba/Ca ratio
[21]	75% CSA clinker + phosphogypsum	Hydration, Setting time, Compressive strength	Different combinations of phosphogypsum with high and low s-P ₂ O ₅ content were added to the CSA clinker	P	The s-P ₂ O ₅ and heavy metals in PG could be effectively immobilized; lowers down the driving force for the precipitation of ettringite; dissolution and hydration of C4A3\$ is also inhibited; prolongs the setting time; lowers down the early age compressive strength and leads to a higher linear expansion rate

Table S-2. Experimental studies on the use of tailings of different origins as a partial replacement for cement.

Reference	Tailings type	SO ₃ content (%)	Major minerals	Activation method	Observations
Choi <i>et al.</i> , 2009 [22]	tungsten tailings	<1.5	quartz, chlorite, anorthite, cordierite	unactivated	loss of flowability and compressive strength with increase in replacement ratio; SCM reaction from tailings was not identified
Peng <i>et al.</i> , 2015 [23]	tungsten tailings	<0.2	garnet, amphibole, chlorite	grinding and 20% activator (lime, gypsum, sodium silicate)	Grinding and lime activation improve compressive strength; no direct evidence of activation mechanisms
Guo <i>et al.</i> , 2016 [24]	pyrite tailings	5.41	kaolinite, anatase, calcite, pyrite	calcination at 700-900°C and grinding	Calcined and ground tailings showed high pozzolanic activity; all replacement ratios (5-40%) contributed to improvement in strength; optimum replacement ratio is 20% wt.; optimum fineness is d ₉₀ =12µm; workability of concrete was impaired with increasing tailings %
Vargas and Lopez, 2018 [25]	08 different copper tailings (from ongoing operation and long-standing)	<2.6	quartz, albite, zinc oxide, cristobalite, kaolinite, montmorillonite, dolomite, calcite, feldspar	calcination at 600-800°C and grinding	Varied chemical composition and physical properties affect performance in different ways; case-by-case analysis is required to determine reactive potential. The effect of thermal treatment is more significant at later ages, while effect of grinding is more significant at early ages. Decomposition of clay minerals increased pozzolanic activity of treated tailings
Simonsen <i>et al.</i> , 2020 [26]	13 different tailings from metal and industrial mineral mines	<3.25		unactivated	All tailings studied have significantly different properties. Reactive potential for low strength application screened by chemical composition, mineralogy, and physical properties
Magalhaes <i>et al.</i> , 2020 [27]	iron ore tailings	-	quartz, hematite, goethite, kaolinite	calcination at 500-750°C	Decomposition of kaolinite due to calcination was not sufficient to improve compressive strength (0-30% replacement level); strong colour differences due to conversion of goethite to hematite
Ramanathan <i>et al.</i> , 2021 [28]	Ni-Cu tailings	0.3	tremolite, clinocllore, siderophyllite	grinding	Disc-milled tailings showed reduction in d ₅₀ and increase in amorphous content. Higher heat release, although still in the inert material zone, was observed in a modified R3 test, and slight portlandite consumption in cement pastes when replacing 30% of PC

Table S-3. Alkali activated co-binders produced from mine tailings with other side streams.

Reference	Type of MTs	Co-binder	S content in MTs	Pre-treatment	Alkali activator	Aggregates	Curing conditions	Observations
Zhang et al. [29]	Copper mine tailings	Fly ash (FA) (0-100%)	1.66%	n.a.	Sodium hydroxide solution (5, 10, 15M)	n.a.	60 °C	Si/Al, NaOH concentration, and curing time considerably affect geopolymerization of the co-binder. The compressive strength can be controlled by adjusting the content of fly ash, varying from 1.37 MPa to 21.2 MPa.
Ahmari et al. [30]	Copper mine tailings	Cement kiln duct (CKD) (0-10%)	1.66%	n.a.	Sodium hydroxide solution (10, 15M)	n.a.	90 °C, forming pressure	CKD can significantly improve the physical and chemical properties of geopolymer bricks, which meets the lowest standard limit of ASTM. CKD can promote the geopolymerization of co-binders. CaCO ₃ formed, and it coexists with geopolymeric gels.
Falayi et al. [31]	Gold mine tailings	FA and blast oxygen furnace slag (BOF) (0-50%)	3.05%	n.a.	Potassium hydroxide solution (5, 10, 15M)	n.a.	Ambient condition and 50-90 °C	FA and BOF slag can modify mine tailings based geopolymers, where slag-MT geopolymers requires a lower curing temperature than that of FA-MT based mine tailings. Elevated curing temperature can enhance the performance of co-binders. Both FA and BOF modified MT-geopolymers meet the acceptable limits for static leaching tests.
Duan et al. [32]	Iron ore mine tailings	FA (30%)	n.a.	n.a.	10M sodium hydroxide and sodium silicate solution	n.a.	Ambient condition	Porous FA-MT based geopolymer was synthesized with high total porosity of 74.6%. It achieves 90.7% removal efficiency. The initial Cu ²⁺ concentration, pH, contact time, and temperature are main factors.
Kiventerä et al. [33]	Gold mine tailings	ground granulated blast furnace slag (GGBFS) (0-100%)	5.2%	n.a.	Sodium hydroxide (5, 10, 15M)	n.a.	Ambient condition	Pristine MT based geopolymer can reach a compressive strength of 3.5 MPa. 5% additive of GGBFS can increase the compressive from 1.3 MPa to 4.4 MPa with 5M NaOH solution. 25% GGBFS modified MT geopolymer achieves a 25 MPa at 28 days compressive strength with 5M NaOH solution. Leaching test is required in the future investigation.
Kiventerä et al. [34]	Gold mine tailings (40-50%)	GGBFS (20-30%) + metakaolin (MK) (30%)	5.2%	n.a.	Sodium hydroxide solution (8, 9M), sodium silicate solution	n.a.	Ambient condition	A high immobilization efficiency was achieved for main elements such as (Cr, Cu, Ni, Zn, and Mn). A better performance can be seen for a longer curing at 28 days. The problematic oxyanions such as (As, Sb, B, and V) can be highly immobilized after 7 and 28 days curing in terms of pristine mine tailings.

Kiventerä et al. [35]	Gold mine tailings	GGBFS (10-25%)	3.9%	Vibratory disc mill 2 min at 1000 rpm; thermal treatment at 900 °C for 6 h.	Sodium hydroxide solution, sodium silicate solution, 5 % Ca(OH) ₂ solution	n.a.	Room temperature with RH 90%	Sulfates and arsenic can be efficiently stabilized in the co-binders after 7-days curing. Thermal treatment can increase reactivity of mine tailings; however, there is no significant influence on heavy metal stabilization. The formation of Ca(AsO) ₂ was found due to the additive of Ca(OH) ₂ .
Jiang et al. [36]	Gold mine tailings	OPC+ slag	0.45%	n.a.	Sodium hydroxide and sodium silicate	n.a.	RH 95±1% for 24h, followed by 30 and 40 °C, RH 80±2%	Decreased workability and increased compressive can be seen with more solid content. 8% of binder dosage gives a favorable 3-day compressive strength of 1.34 MPa. The highest compressive achieved at an alkali activator/binder at 0.3. Sodium silicate/sodium hydroxide slightly effects workability, while compressive strength is largely depending on the curing time. Elevated curing temperature improves the performance of compressive strength.
Cihangir et al. [37]	Copper-zinc mine tailings	OPC + blast furnace slag	40.7%	n.a.	Sodium hydroxide and sodium silicate	n.a.	RH 85±1% , room temperature 20±1 °C	The introduce of slag can improve the mechanical strength and stability performance due to the high pH (≥ 10.7). A lower content of Ca results in less formation of gypsum. The alkali activator type and curing time have major effects on physical and chemical properties of co-binders.
Manjarrez et al. [38]	Copper mine tailings	Low Ca slag (0-50%)	n.a.	n.a.	Sodium hydroxide solution (5, 10, 15M) + sodium silicate	n.a.	45 °C, 53 °C, 60 °C, 68 °C, and 75 °C, respectively	The optimal w/s ratio of 0.158 can be seen for co-binders. Slag can improve the mechanical performance of co-binder, while the ratio of sodium silicate and sodium hydroxide matters. A higher sodium hydroxide concentration of 15M significantly decreases workability. The behavior of Fe should be considered during geopolymerization.
Ahmari et al. [39]	Copper mine tailings	Smelt slag (0-100%)	1.66%	n.a.	Sodium hydroxide	n.a.	60, 75, 90, and 105 °C, forming pressure 0.5-3 MPa	Low calcium smelter slag modified mine tailings geopolymers possess higher mechanical performance. A higher content of slag requires a lower curing temperature. The co-binder has a fast setting time, and the major compressive strength obtained after only 7 days.

Wu et al. [40]	Copper mine tailings	Metakaolin (40, 50, 60%)	n.a.	n.a.	Sodium silicate solution (6.17M)	n.a.	60 °C for 12h and room temperature until testing	Heating-cooling cycle promotes the formation of N-A-S-H gel. Si/Al significantly changes the backbone of N-A-S-H gel due to different components of metakaolin. The evolution of geopolymerization was evaluated for the purpose of marine concrete with tailings.
Wan et al. [41]	Mine tailings from sphalerite flotation	Metakaolin (0-50%)	1.46%	n.a.	Sodium silicate solution	n.a.	60 °C for 6h and room temperature until testing	The highest compressive strength can be found at 17.3 MPa. When the additive of Pb(NO ₃) ₂ is less than 6%, a higher compressive can be seen due to the formation of lead silicate glass, whilst a lower compressive strength was obtained when the content of Pb(NO ₃) ₂ is higher than 6%. Co-binder generates geopolymeric gel which is able to efficiently immobilize lead.
Paiva et al. [42]	Copper and zinc mine tailings	BFS and metakaolin (0, 50, 62%)	26.18%	n.a.	Sodium hydroxide (10M)	n.a.	RH 65±5% , room temperature 20±5 °C	Mine tailings are fine aggregates in this co-binder. The author concluded that MTs are quite inert and did not act as geopolymer precursor. Metakaolin based geopolymer obtains a good compressive strength of > 20 MPa. The geopolymerization was evaluated by rheology measurement. Geopolymers with high MTs content show good chemical resistance even after testing in a lower pH condition for 40 days.
Ren et al. [43]	Copper mine tailings	Aluminum sludge (AG) (0, 10, 20%)	2.22%	n.a.	Sodium hydroxide	n.a.	90 °C, 0.5 MPa forming pressure	By adding AG, there is clear enhancement seen in the final co-binders. A favorable compressive strength of 44.8 MPa was reached after optimizing recipe. AG can modify the Si/Al and accelerate the geopolymerization process.
Defăveri et al. [44]	Iron ore mine tailings (IOT)	Glass wool residues (GWR)(0-30%)	n.a.	Grinding of IOT for 1, 2, and 3h	Sodium hydroxide (8, 10, 12M)	n.a.	100 °C	The MTs based geopolymer shows promising compressive strength and flexural strength for 112.8 MPa and 21.3 MPa for 7 days, respectively. However, the additive of glass wool residues can decrease the mechanical performance of co-binders. Chamosite and chantalite participate in geopolymerization, while other minerals are inert. GWR facilitates the formation of C-S-H in geopolymers.
Kasiukas et al. [45]	Tungsten mine tailings	Waste glass (0-40%)	8.72%	n.a.	Sodium hydroxide (10M), sodium silicate	n.a.	RH 50%, curing temperature 20-80 °C	Blending with waste glass significantly increases the degree of amorphicity, which is superior to traditional calcination. A longer activator mixing time can reduce the dissolution of the precursor due to less initial alkali metals. The optimal condition was found as 80 °C for 24h.
N.A.: not applicable								

Table S-4. Inorganic polymer (mortar) produced by solo mine tailings.

Reference	Type of MTs	SiO ₂ content	Al ₂ O ₃ content	SO ₃ content	Pre-treatment	Alkali activator	Aggregates	Curing conditions	Observations
Aseniero et al. [46]	Gold mine tailings	52.2% to 77.3%	4.48% to 9.71%	1.13% to 2.31 %	n.a.	Lime sludge + 5M NaOH forming dry powder	n.a.	Ambient condition	A maximum compressive strength of 5.95 MPa. Aluminosilicate clays are playing vital role during geopolymerization. The system can be further developed by additive of other reactive components.
Manjarrez et al. [47]	Copper mine tailings	55.90%	14.10%	2.22%	n.a.	3, 5, 7, and 11M NaOH solution	n.a.	11, 14, 16, 17 and 19% moisture at 35 °C	Both moisture content and concentration of NaOH have significant effect on the performance of resulted samples. The optimized product meets the strength requirement of cement-treated road base; however, it needs further leachate study before case application.
Ahmari et al. [48]	Copper mine tailings	64.8%	7.08%	1.66%	n.a.	10 and 15M NaOH solution	n.a.	Curing temperature 60 to 120 °C, water content 8% to 18%, forming pressure 0 to 35 MPa	The highest compressive strength was achieved at 33.7 MPa. The specimens prepared at 15M NaOH express higher compressive strength than those at 10M. Forming pressure is essential without squeezed water out the mold. 90 °C is the optimal curing temperature in this work.
Pacheco-Torgal et al. [49]	Tungsten mine tailings	53.48%	16.66%	3.10%	Thermal treatment (650 to 950 °C) up to 480 min	12M NaOH solution, sodium silicate solution and calcium hydroxide	Sand	Ambient condition	Tungsten mine tailing is a promising candidate for geopolymerization with lower carbon footprint. A bright perspective can be seen for tailing-based geopolymer mortar since its overall cost is similar or even under that of M9 geopolymeric fly ash-based concrete.

Pacheco-Torgal et al. [50]	Tungsten mine tailings	53.48%	16.66%	3.10%	Thermal treatment (950 °C, 2h)	24M NaOH solution, sodium silicate solution, calcium hydroxide powder	Schist sand, limestone, and granite	Ambient condition	The workability and setting time were not possible to assess the tailings-based binder due to the adhesion with device and paste-mortar difference. A lower water absorption was observed. The resulted mortar has aligned static elastic modulus compared with other researches. A long-term curing of the mortar with proper additive of superplasticizer leads to a higher compressive strength more than 80 MPa.
Pacheco-Torgal et al. [51]	Tungsten mine tailings	53.48%	16.66%	3.10%	Thermal treatment (950 °C, 2h)	24M NaOH solution, sodium silicate solution, calcium hydroxide powder	Coarse aggregates	Ambient condition	Tailings-based geopolymer binder shows a high bond strength with OPC concrete surface. The setting condition of geopolymer binder is superior to commercial products which requires proper curing conditions. Form the viewpoint of cost, the geopolymeric ones are the most efficient according to the research.
Pacheco-Torgal et al. [52]	Tungsten mine tailings	53.48%	16.66%	3.10%	Thermal treatment (range from 450 to 1100 °C) with sodium carbonate	12M NaOH solution, sodium silicate solution and calcium hydroxide	Sand	Ambient condition	The additive of sodium carbonate leads to a lower early-stage compressive except optimal thermal pretreatment temperature. Sodium carbonate may cause unbalanced chemical combination and slat efflorescences after waster immersion compared with pristine mine tailings-based geopolymer mortar.
Falah et al. [53]	Ni/Cu mine tailings	47.96%	3.99%	0.15%	Grinding of MT to a grain size lower than 5 µm	Sodium silicate solution	n.a.	40 and 60 °C	Sodium silicate concentration, curing temperature/time have significant effect on the compressive and microstructure of final geopolymers. The optimal compressive strength can be achieved for the 28 days curing samples at 60 °C.
Koohestani et al. [54]	Cu/Zn mine tailings	44.71%	5.18%	37.65%	n.a.	Sodium silicate solution	n.a.	Ambient condition	Sodium silicate concentration has significant effect on the curing behavior of tailings-based geopolymer. Increased pH can delay the hardening process. There is no geopolymeric gel observed at the pH

									lower than 11. Only silica gel network contributes to the strength acquisition.
Yao et al. [55]	Gold ore tailings	72.86%	13.68%	0.16	Planetary mill for 20-80 min	Anhydrite, CaO	n.a.	20 °C with relative humidity above 95%	The final products reach a 28 days compressive strength of 4.12 MPa and an activity index of 78.99%. Mechanical activation is feasible to improve the pozzolanic reactivity, showing an effective approach to upscale mine tailings sustainably.

N.A.: not applicable

Table S-5. Research studies on the production of building ceramics from mine tailings.

Reference	Tailing material (wt%)	Other mixed materials	S/SO ₃ tailing content (wt%)	Building ceramics application	Production conditions	Main conclusions
Abi et al., 2011 [56]	Coal tailings (0-50)	Primary clay	SO ₃ (0.22) from tailings:clay mix	inner-wall bricks/blocks	Fired 850-1050°C for 2 h	Up to 15 wt% tailings integration gave satisfying mechanical and chemical properties at higher sintering temperatures (950°C and 1050°C)
Lavrinenko et al., 2018 [57]	Coal tailings (0-40)	Clay mixture	S (0.43) from tailings and S (0.15) from tailings:clay mix	bricks	Fired 900-1150°C	20 wt% tailings integration increased porosity and consequently heat-insulating properties and decreased shrinkage
Stolboushkin et al., 2016 [58]	Coal tailings (60-100)	Clay loam	not reported	bricks	Fired 1000°C	70-80 wt% of tailings gave high physical and mechanical properties, and, after coal waste secondary processing, generating additional energy for brick factories
Stolboushkin et al., 2016a [59]	Coal tailings (70)	Loam	not reported	bricks	Fired 600-1200°C	Good amount of pyroclastic glass phase for ceramic brick sintering at a temperature between 950-1050°C
Stolboushkin et al., 2016b [60]	Coal tailings (65)	Loamy clay, crushed glass	not reported	bricks	Fired 900-1000°C	65:25:10 ratio of tailings:loam:glass showed advanced physical and mechanical properties by the matrix structure, intensive glass-phase formation, and temperature reduction of the solid-phase sintering
Taha et al., 2017 [61]	Coal tailings (60-100)	Shale	S (0.21)	bricks	Treated coal mine tailings by froth flotation; pressing 6 MPa; Firing mixtures at 1020°C for 5h	Up to 100 wt% treated coal tailing bricks where in agreement with ASTM requirements; higher mechanical strength than reference; leached metals from environmental assessment under limit requirements of Building Material Decree and US-EPA regulations
Chen et al., 2011 [62]	Hematite tailings (77-100)	Clay, Fly ash	not reported	bricks	Fired 980-1030°C for 2h	84:10:6 ratio of tailings:clay:fly ash achieved satisfying technical properties in compliance with China standards for fired common bricks (GB/T5101-2003)
Chen et al., 2013 [63]	Hematite tailings (50-70)	Kaolin, Quartz sand	not reported	porcelain red tiles	Fired 1150-1250°C for 30 min	55-65:25:10-20 ratio of tailings:kaolin:sand integration fired at 1200°C showed satisfying sintering and high

						crystallinity of the main mineral phases. It also presented low porosity of solid solutions in a dense glassy and crystalline phase, as well as compliance with Chinese standards for ceramic tiles (GB/T4100-2006 2006)
Zhao et al., 2012 [64]	Hematite tailings (70)	Lime, Sand, Gypsum	SO ₃ (0.24)	bricks	Autoclaved at 1.2 MPa for 6 h	70:15:15 ratio of tailings:lime:sand satisfied Chinese requirement (GB11945-1999) for MU20 autoclaved bricks
Salinas-Rodríguez et al., 2017 [65]	Silver-Gold tailings (55-65)	Black clay, Aggregates	not reported	bricks	Fired 1100°C for 1h	Au-Ag tailings can be used as feldspar substitutes giving similar or better technical properties than those of a conventional brick
Flores-Badillo et al., 2015 [66]	Silver-Gold tailings (not reported)	Heavy clays	not reported	roof tiles	Molding, dried at room temperature, and green sintering	Up to 55 wt% of Ag-AU tailings showed satisfying grain size distribution and natural colors
Roy et al., 2007 [67]	Gold tailings (0-80)	Red-soil	not reported	bricks	Fired 750-950°C for 9h	45:55 ratio of tailings:red soil assured the required technical criteria for compressive strength, linear shrinkage, and water absorption. Soil-tailing bricks would be 0.85 times the cost of conventional clay bricks
Yonggang et al., 2011 [68]	Gold tailings (25-75)	Clay mixtures	Medium tailings (S= 2.07 wt%) and fine tailings (S= 3.21 wt%)	bricks	Press forming (15 Mpa, 8-9 wt% water) and fired 1050°C for 1h	75:25 ratio of fine tailings:clay, and 25:75 ratio of medium tailings:clay achieved compressive strength of MU10, with no lime blowing or efflorescence occurring
Shao et al., 2005 [69]	Gold tailings (60-65)	Alumina, magnesia, and SB2O3 and NH4NO3 as fluxing agents	SO ₃ (0.38)	glass ceramics	Glass preparation included melting at 1550°C for 2h, 300°C hot stainless steel plate, annealing furnace 500°C for 1h	Feasible raw material for cordierite-base glass-ceramics showing satisfying mechanical properties comparable with the industrial standard cordierite
Belmonte et al., 2018 [70]	Gold (20-40) and rare-earth (20-40) tailings	Marine clay	not reported	bricks	Fired at 1000°C for 1h	Open porosities and densities acceptable for brick production but leaching tests (DS/EN 12457-1) showed high mobility of As, Pb and Zn, non-compliant with Danish environmental regulations
Peng et al., 2014 [71]	Tungsten tailings (72)	Silica, Alumina, CaCO ₃ , Na ₂ CO ₃	not reported	glass ceramics and tiles	Glass preparation melting at 1400°C for 3h, nucleation for 2h followed by melting 950-1100°C for 2h	Gehlenite–hedenbergite glass-ceramics prepared from tungsten tailings showed proper crystal structure and high performance at 1050°C
Li et al., 2020 [72]	Tungsten tailings (not reported)	SiO ₂ , Na ₂ CO ₃ , CaO, Al ₂ O ₃ , BaO, B ₂ O ₃	not reported	glass ceramics	Tailings were calcined at 600°C for 2h and glass preparation included melting at 1530°C for 2h	Glass-ceramic fired at 950°C for 2h showed good technical properties and moderated acid resistance and lower alkaline resistance. The prepared glass ceramics with tungsten tailings were below Chinese leaching limits (GB 5085.3-2007) and can be considered as non-toxic to the environment

Wu et al., 2016 [73]	Tungsten tailings (100)	-	S (0.18)	floor and wall tiles	Fired 1000-1100°C for 1h and 1050°C from 0-2h	Pure tungsten tiles showed good sintering properties at temperatures below 1050°C, excellent properties are achieved at firing temperature of 1050°C for 1h. Recycling W tailings at low sintering provide a cost-effective solution for high strength ceramics
Das et al., 1996 [74]	Iron ore tailings (not reported)	Fly ash, blast furnace slag + alumina, aluminosilicates (additives)	not reported	floor and wall tiles	Vitrification	Tiles showed high strength and hardness compared to conventional tiles and conform with European Standards. Energy and cost efficiency were also achieved
Das, et al., 2000 [75]	Iron ore tailings (30-50)	Clay + fluxing minerals	not reported	floor and wall tiles	Air-fired 1060-1250°C	Up to 40 wt% of silica-rich iron tailings showed high hardness and strength, comparable to EN standards. Cost-effective solution
Das et al., 2012 [76]	Iron ore tailings (45-60)	Clay, Feldspar	not reported	floor and wall tiles	Fired 1100-1150°C for 1h	Tiles fired at 1150°C showed high strength. Fine iron tailing and its strong fluxing action, there is less energy consumed compared to conventional tiles processing
Jian et al., 2011[77]	Iron ore tailings (not reported)	Rock waste	SO ₃ (0.2)	wall materials	Sintering 850-950°C	High plasticity achieved in vacuum extruded mold can lead to shrinkage cracking. Water absorption, apparent porosity, and bulk density did not change significantly
Li et al., 2019 [78]	Iron ore tailings (not reported)	Acrylamide (AM) and N, N'-Methylene-bis-acrylamide (MBAM), Tetramethylethylenediamine (TEMED), ammonium persulfate (APS) + Lauryl alcohol, and sodium dodecyl sulfonate (SDS)	not reported	porous bricks	Hydrous foam-gel casting method and sintering 1070-1120°C for 3-11h	High strength and low thermal conductivity are achieved in porous bricks. Relationship between compressive strength and porosity of porous bricks matches the Gibson equation
Mendes et al., 2019 [79]	Iron ore tailings (0-50)	Yellow clay	SO ₃ (1.44)	bricks	Firing 850°C for 3h	Incorporation of iron tailings gave good mechanical properties, decreased water absorption, apparent porosity, and firing shrinkage. Another experimental design is recommended to meet all criteria

Marabini et al., 1998 [80]	Chromite (70) and talc (60) tailings	Basalt	not reported	glass ceramics	Melting 1350°C, 600°C steel plate and crystallization 800°C for 6h	Good hardness and mechanical strength as well as resistance to chemical attack due to immobilization of heavy metals in crystalline phases
Fang, et al., 2011 [81]	Copper tailings (40-88)	River sand, Sand powder, Lime	SO ₃ (1.79)	bricks	Autoclaved at 20 MPa, at 170-180°C for 5-9h	Up to 50 wt% copper tailings integration in autoclaved brick (180°C, 7-9h) have higher strength than required (MU 15 autoclaved brick of GB11945-1999). Radioactivity of the brick was compliant with GB 6566-2001 limitations.
Taha et al., 2017a [82]	Lead (calamine) tailings	Shale, glass waste	SO ₃ (24.6)	bricks	Treated lead tailings by flotation; pressing 6 MPa, firing at 1020°C	Up to 30 wt% of treated lead tailings and 10 wt% of glass waste incorporation in shale bricks showed suitable physical and mechanical properties. However, leaching tests (TCLP) on fired bricks showed high mobility of Pb, above the established limit.
Veiga Simão et al., 2021 [83]	Copper-lead-zinc tailings (5-10)	Clay mixtures	S (9.6)	roof tiles and blocks	65°C industrial drying, roof tiles (fired at 985°C and 1000°C for 2h) and blocks (fired at 965°C for 30 min.)	5 wt% (roof tiles) and 10 wt% (blocks) integration of Cu-Pb-Zn tailings arise technical and aesthetical issues. Tailing material cannot be used as non-shaped building material (aggregates) due to the high leachability of Cd, Cu, Ni, Pb, and Zn (above regulation limits)
Liu et al., 2017 [84]	Lead-zinc tailings (30-70)	Fly ash	SO ₃ (18.96)	porous ceramics	Tailings and fly ash calcined at 120°C, pressed mix at 20 MPa, fired 1200°C for 2h in air-atmosphere	Up to 40 wt% of Pb-Zn tailings improved chemical stability due to the formation of more glass phase content
Veiga Simão et al., 2021 [83]	Lead-zinc tailings (5-10)	Clay mixtures	S (0.01)	roof tiles and blocks	65°C industrial drying, roof tiles (fired at 985°C and 1000°C for 2h) and Blocks (fired at 965°C for 30 min.)	5 wt% (roof tiles) and 10 wt% (blocks) integration of poor Pb-Zn tailings gave comparable technical, aesthetical, and chemical properties to the standard. Tailing material can also be used as non-shaped building material (aggregates) as it follows regulation limits
He et al., 2012 [85]	Niobium-tantalum tailings (77-82)	Cao, ZnO, BaO	not reported	glass ceramics	Heating at 600°C for 2h in air, followed by melting at 1500°C for 2-3h.	With CaO the intensity of crystal diffraction peaks increase. Glass ceramics prepared with a two-step sintering present density and sintering quality
Baowei et al., 2013 [86]	Rare-earth element tailings (10-50)	Fly ash, hematite, and alumina	not reported	glass ceramics	Melting at 1470°C for 4h, followed by annealing at 600°C for 3h.	50:20 ratio of tailings:fly ash excellent overall performance with high chemical resistance, viable for use as an engineering material

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