Recycling Mine Tailings as Precursors for Cementitious Binders – Methods, Challenges and Future Outlook

S. Maruthupandian, A. Chaliasou, A. Kanellopoulos[*]

University of Hertfordshire, School of Physics, Engineering and Computer Science, Centre for Engineering Research, College Lane Campus, Hatfield, AL10 9AB, United Kingdom
Email: a.kanellopoulos@herts.ac.uk

Abstract

Increase in demand for mineral commodities such as coal, copper, iron, aluminium, gold, tungsten, zinc etc., has led to higher quantity of mineral waste produced such as solids, crushed rocks, overburden soil and tailings. The fine-grained mineral waste left after removal of valuable material from ore is called mine tailing and is one of the major wastes of the mining processes. Mineral wastes from mines, quarries and excavations are typically rich in SiO_2, Al_2O_3, CaO and Fe_2O_3. This chemical composition makes them very attractive candidates to be used in the production of construction materials, as these oxides are also the main constituents of cement as well as of key alkali-activated binders. This contribution aims to provide a comprehensive overview of the nature of mine tailings, the current state-of-the-art in their utilisation in cementitious binders and the future potential. A rational summary of limitations associated with use of mine tailing in cementitious binder due to its low reactivity and potential solutions to overcome it is also provided. The study concludes with how the use of mine tailings in cementitious binder could benefit in achieving the global sustainability goals.

Highlights
- o Up to 2060 rapid growth is expected for construction materials.
- o Decarbonisation policies will lead in the reduction of volumes of traditional SCMs.
- o Tailings' chemical profile yield them suitable alternative cementitious materials.
- o Systematic round-robin studies are required to explore tailings' potential

Keywords:
Mine tailings, mineral waste, alkali activation, thermal activation, mechanical activation, concrete technology

Nomenclature
OECD - Organisation for Economic Co-operation and Development
SCM – Supplementary cementitious material
PC – Portland cement
OPC – Ordinary Portland cement
GGBFS – Ground granulated blast furnace slag
TEM – Transmission electron microscope
SEM - Scanning electron microscope
SDG – Sustainable Development Goal
XRD - X-Ray Diffraction

1. Introduction

The use of natural resources has been the basis of growth in civil infrastructure for at least 100 years. At the same time, the exploitation of natural resources and the pollution associated with their extraction and processing have been already stretching the limits of our natural habitat, putting significant pressure on the environment and human well-being. According to the United Nations, the world's urban population has quadrupled since the 1950s, reaching 4 billion today, and with an estimated 7 billion people living in cities by 2050 [1]. To sustain this rapid urbanisation rate, billions of tonnes of construction materials are required annually.

All evidence and projections suggest that civil infrastructure growth will keep expanding to meet the needs of modern urban societies, including essential development for poverty reduction and provision of fundamental infrastructure to the billions currently living in deprived areas, for the decades to come. A recent report from the Organisation for Economic Co-operation and Development (OECD) projects a rapid growth in the production and use of construction materials in the next 40 years [2]. This translates into a massive demand for pristine natural raw materials. Such demand will have a detrimental effect on the environment, depleting natural resources and causing large scale destruction of landscapes [3].

The manufacture of construction materials is a process that utilises enormous amounts of raw materials and energy, due to the sheer scale of the industrial processes required. Concrete is the dominant construction material and the key element in most infrastructure assets. However, concrete manufacture on a gigatonne scale per annum imposes extremely high energy and resource demands: with >4 billion tonnes of cement being produced annually, accounting for ~8% of global anthropogenic CO_2 emissions, and yielding an annual production of ~2 tonnes of concrete for every person on the planet [4]. In Europe, the construction sector alone is responsible for 36% of CO_2 emissions and for the 40% of all energy consumption [5]. Cement manufacture is a major contributor with the whole clinkerisation process consuming ~3.5 GJ/ton [6].

At the same time, with increase in demand for mineral commodities such as coal, copper, iron, aluminium, gold, tungsten, zinc etc., the mining of ores has increased while low grade ores have started being explored [7]. The lower the quality of the ore, the higher is the quantity of waste produced such as solids, crushed rocks, overburden soil and tailings. The fine-grained mineral waste left after removal of valuable material from ore is called mine tailing and is one of the major wastes of the mining processes.

Mine tailings can be generally disposed by either direct or indirect methods. The former involves disposal of tailings in rivers/seas, while the latter encompasses disposal of tailings in form of slurry (25-30% solid) into a cell, confinement or dam [8]. Mine tailing management is a crucial issue as the physicochemical characteristics of the wastes have severe impact on the soil and ground water including acid mine drainage [9]. The tailings are mainly composed of oxides of silicon, aluminium, calcium, magnesium, and iron. This composition is similar to that of widely used building materials such as cement, fine and coarse aggregates and supplementary cementitious materials. This, in addition to their vast quantities, gives scope for exploring the use of mine tailings in the construction industry.

2. The Challenge for Civil Infrastructure

Despite their heavy carbon footprint, shifting away from conventional cements is difficult. Concrete and the related cement-based materials are the construction industry's favourites for a variety of reasons including: (i) ease and low cost of construction compared to alternatives (e.g., steel); (ii) robustness under a variety of exposure scenarios; (iii) ability to construct a large variety of complex geometries; (iv) excellent mechanical performance, and (v) the almost global abundance of raw materials to produce them. Limestone and argillaceous materials (silica, alumina, iron) are extracted from the earth's crust, and through an intensive thermomechanical process converted to clinker, which is ground to be sold as cement. Then potable water and good quality natural aggregates are added to produce concrete. To satisfy this vast demand for concrete production globally, approximately 27 billion tonnes of natural aggregates and nearly 3 billion tonnes of fresh water are required [10]. The environmental impact with respect to depletion of natural resources is enormous. The International Energy Agency in its recently published roadmap for a sustainable transition in the cement and concrete industries has strongly highlighted two important elements: (i) the need to switch to alternative raw materials by 2025 and (ii) to switch to alternative cementitious binders by 2035 [11]. This strategy is also promoted by the European Cement Association in its latest report on decarbonisation of cement [12].

Reducing the environmental impact of cement-based materials is the focus of research the last 15-20 years. At the forefront of these attempts is the use of supplementary cementitious materials (SCMs). These are typically rich in silica and are soluble siliceous, alumino-siliceous, or calcium-alumino-siliceous fine powders that can be used as partial clinker replacement in cements or as partial replacement of Portland cement (PC) in concrete mixtures. SCMs are by-products of industrial operations (e.g., coal fired power plants; steel industry; ferrosilicon industry) and their chemical structure and mineral nature makes them compatible with the cementitious matrix. The three-best known SCMs are fly ash, ground granulated blast furnace slag, and silica fume. These materials do not directly reduce the environmental impact of clinker, but they rather reduce the need for it. In fact, recent studies show strong indications that the use of such minerals to reduce the clinker demand is the most viable option for the industry [13]. However, several problems that are summarised below are associated with the existing SCMs:

(i) Even though SCMs currently account for about 20% of cementitious materials within the UK cement and concrete industries [14], the global reduction in emissions as a result of SCMs use is not more than about 10% [11]. This signals that more amounts are needed and more efficient material use is necessary.

(ii) The existing SCMs rely heavily on specific industrial waste mainstreams which are currently either under major revision or threat. Coal combustion processes which lead to the production of fly ash are expected to considerably reduce to meet the global demand for lower CO_2 emissions, and biomass combustion or co-combustion products are not as suitable for use in most concretes. In the UK it is planned to retire all coal-fired power plants by 2025 and in the Netherlands by 2030 [15]. It is apparent that the global production of fly ash is expected to decline significantly.

(iii) The existing SCMs are not as abundant as natural raw resources. In addition, they are not readily available in large quantities around the world. This results in either excessive use of

144 cement (in absence of SCMs) or the generation of more CO_2 emissions associated with
145 transportation of such compounds in locations where they are not available.

146

147 On the other hand, billions of tones of mineral wastes (from mines, quarries, and excavations)
148 are produced globally every year. For mine tailings alone this quantity is estimated to be in the
149 range of 5 to 7 billion tonnes [16]. Recent studies suggest that the stock of mine tailings
150 generated in China only since 2013 has reached almost 15 billion tonnes [17]. The disposal
151 of such waste is a major environmental challenge and liability, especially in the light of some
152 recent disasters involving the collapse of mineral waste dams leading to considerable loss of
153 life and ecological damage [18–20]. In addition to such catastrophic events, stockpiling such
154 vast amounts of wastes can significantly alter the natural habitat and the biodiversity of the
155 surrounding areas [21].

156

157 Mineral wastes from mines, quarries and excavations are typically rich in SiO_2, Al_2O_3, CaO
158 and Fe_2O_3. This chemical composition makes them very attractive candidates to be used in
159 the production of construction materials, as these oxides are also the main constituents of
160 cement as well as of key alkali-activated binders. The last two years there is a growing interest
161 in utilising such wastes in the manufacture of cement-based composites, alkali-activated
162 binders and ceramics [16,22,23].

163

164 The use of mine wastes in cements can offer a natural solution to a major problem while at
165 the same time their own environmental impact is mitigated. Recycling such wastes in the
166 production of widely used materials is the most promising way to maintain our natural reserves
167 of raw materials and significantly reduce CO_2 emissions associated with the clinker (or other
168 binder) demand. In addition to the predictions from the International Energy Association and
169 the European Cement Association mentioned earlier, the World Business Council for
170 Sustainable Development also considers the recycling of certain mineral wastes as SCMs a
171 very promising solution towards a sustainable future [24].The World Economic Forum and
172 OECD in their recent reports emphasise that recycling of mineral wastes will gradually become
173 more competitive than mining minerals and the global volumes for mineral waste recycling are
174 expected to grow considerably by 2060 [2,25]. Nonetheless, this process has limitations and
175 unknowns. The variability in waste streams calls for detailed and focused research on this
176 area. This is essential to thoroughly understand the different mineralogical and chemical
177 characteristics of these compounds and hence being able to identify optimum pathways for
178 their use and exploitation in construction materials manufacturing.

179

180 The present work discusses the physical, mineralogical, and chemical properties of different
181 mine tailings and the influence of the mineral composition on their behaviour. The activation
182 of mine tailings based on the mineral composition rather than a conventional chemical
183 composition is assessed in detail. It was observed from past studies that minerals of different
184 reactivity and crystalline structure had same chemical composition and behaved different
185 when used in cementitious binders [26,27].

186

187 The current contribution reviews past studies on the utilisation of mine tailings in cementitious
188 (and "cement-like") matrices. This includes studies that used mine tailings as SCMs, as a raw
189 material for clinker, as direct cement replacement (with or without activation) and alkali
190 activated binders. For this purpose, scientific articles were collected by combination keyword
191 searches on data bases such as the Web of Science, Google Scholar, Scopus. Mine tailings,

mine waste, mine sludge, mineral waste, thermal activation, mechanical activation, alkali activation, geopolymerisation and valorisation of mine tailings were used as key words selected based on the abstract and title. Screening of published works was done to avoid repetition and duplication. Though the papers on masonry units and other civil engineering applications (e.g., the use of wastes as aggregate replacement) are reported only the activation process and the properties of the mine tailings were considered from those studies as anything else was beyond the scope of this paper. The studies confining to cementitious binders ranging only from 2000 to 2021 have been taken into consideration for the review. Figure 1 below summarises the steps followed in this analysis.

Fig. 1: Summary of steps followed to obtain the data discussed in this study.

3. Mine Wastes

3.1 Sources

Mining is the term used to describe the process of excavation of earth's crust to extract minerals and ores. Valuable components or metals are extracted from the minerals and ores by different mineral separation processes. At the end of the mineral separation process, a valuable component, which is a concentrate of base metal or mineral, is extracted. As part of this process, the mineral separation process residues (tailings) are generated [28]. Tailings do not bear any significant monetary value and occur in form of sludge with a varying water content ranging from 18 to 32% [29–32]. The quantity of tailings generated varies, depending on several factors: (i) the type of material extracted; (ii) the process followed and (iii) the quality of ore. Ince et al [33] reported that for low quality ores in copper extraction about 128 tons of tailings are generated for the production of 1 ton of copper. In the contrary, high-quality ores can generate 1.5 tons of tailings for every ton of copper produced [34]. Nonetheless, even the optimum 1 to 1.5 ratio will lead to the production of immense volumes of waste material that currently remains unused affecting the environment and local communities.

3.2 Physical, Chemical, Mineralogical properties

3.2.1 Physical Properties

Mine tailings are crystalline, relatively loose and porous in microstructure [35]. The specific gravity of such compounds ranges between 2.70 – 4.29, depending on the type of mine and its composition [36–38]. Mine tailings are reported to have a high-water absorption, up to 7.15% [39]. This can raise concerns if the tailings are intended for use in concrete as

228 aggregates. However, such porous materials can have alternative uses. Recent studies have
229 shown that a percentage of highly porous aggregates can facilitate internal curing processes
230 [40,41]. In addition, it has been demonstrated that porous aggregates can be used as carriers
231 for healants in promoting self-healing processes in cementitious matrices [42,43].
232
233 The pH of tailings is generally in near neutral or slightly alkaline region ranging between 8.0 –
234 9.3 for carbonate rich mine tailings [31] and 6.7 – 10.0 for silicon rich mines [30,44,45]. Though
235 the pH of mine tailings is generally alkaline, the chemical and mineral composition of a mine
236 tailing determines the possibility of acid mine drainage. If a mine tailing has high amounts of
237 sulphide minerals and low amounts of minerals such as carbonates, which will neutralize them,
238 their oxidation in natural conditions may also lead to acid mine drainage [46]. If the mine
239 drainage is neutralized, neutral effluents generated may consist of toxic metals and metalloids,
240 such as Ni, Zn, Co, As, and Sb [47]. This makes the effective and efficient recycling and reuse
241 of such wastes a major environmental concern.
242
243 The particle size of tailings varies amongst cement sized, silt sized and sand sized particles.
244 Argane et al., [46] reported a silt sized tailing of D_{50} 210 -270 µm whereas Bussiere [28]
245 reported a cement sized mine tailing of D_{50} 17 µm. The particle size distribution of mine tailing
246 observed in various studies are as given in Fig. 2.
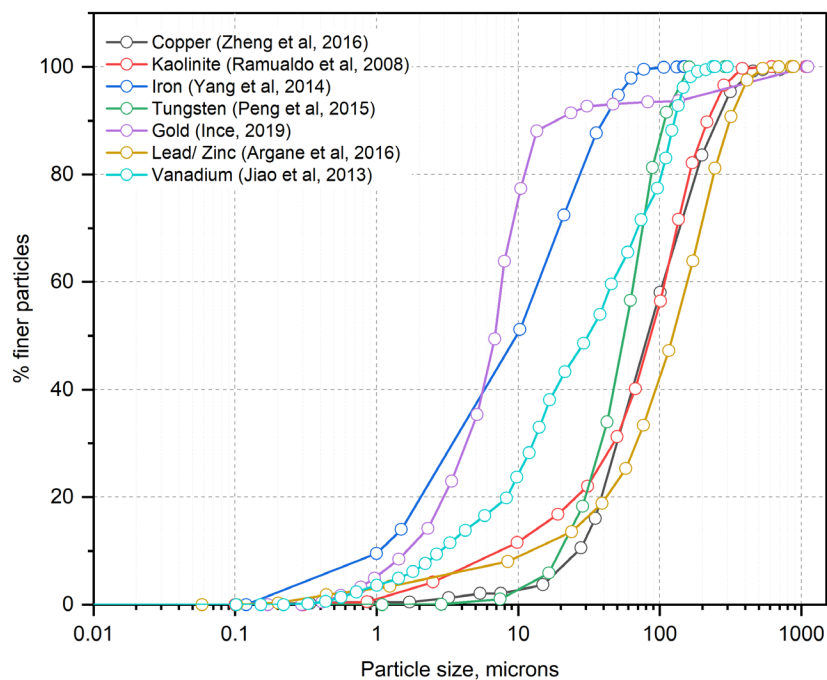
247
248 **Fig. 2:** Particle size distribution of various mine tailings.
249
250 The variation in the size enabled various attempts on recycling the mine wastes as fine
251 aggregates [48,49] and as a binder component [39,50,51]. However, the feasibility of using
252 mine tailings as aggregate or cement mainly depends on its chemical composition, rate of
253 dissolution and its ability to produce hydration products like that of cement.
254
255 3.2.2 Chemical and Mineralogical Properties
256 The composition of mine tailings varies highly due to the variation in source mineral, process
257 of extraction, mineral extracted and quality of the ore. Table 1 shows the chemical composition
258 of various mine tailings discussed across several studies. It can be seen from the table that

259   bauxite, coal, graphite, gold, iron, kaolinite, and lead-zinc tailings are predominantly composed
260   of silicate. Phosphate, tungsten, and zinc tailings have a considerable amount of CaO, whilst
261   bauxite, coal and kaolin tailings have a considerable amount of Al_2O_3. The ratio of silica to
262   alumina (SiO_2/Al_2O_3) of tailings ranges from 0.86 – 9.12, modulus of hydraulicity [52] ranges
263   between 0.02 – 3.98 and the modulus of basicity are between 0.03 – 5.28. Shi et al [53]
264   recommended a basicity modulus range between 0.7 to 1.2 for a material to be suitable for
265   alkali activation. However, these conventional indicators of hydraulicity or geopolymerisation
266   may not be suitable to determine the reactivity of the mine tailings, as the mine tailings are
267   crystalline in nature [48] and aluminates and silicates present are not always available in a
268   form suitable for dissolution that will yield them suitable for participation in chemical reactions.
269   Therefore, the mineralogical composition of the material plays a significant role in determining
270   its reactivity and selection of appropriate and effective treatments can only be done when the
271   fraction of reactive components in a tailing are identified [54].
272
273   Table 2 provides an outlook of various minerals present in different mine tailings. Quartz,
274   Kaolinite, Calcite, Muscovite are some of the minerals most widely found in the tailings.
275   Similarly, many phyllosicate, alumino silicate, calcium alumino silicate and carbonate minerals
276   were also present. It can be seen that SiO_2 is found in non-reactive quartz form [55,56] or
277   reactive cristobalite form [57,58]. Similarly,TiO_2 occurs as low reactive Rutile [26,59] and in
278   the form of anatase which is more reactive [60]. Minerals may also occur as a member of a
279   series such as feldspar, biotite, phyllosilicates, iron oxides, alumina silicates, with different
280   crystallinity and reactivity [61,62]. Hence, conversion of non-reactive phases to reactive
281   phases and making them more amorphous is important for exploring the potential of mine
282   tailing as binders.
283
284

Table 1: Chemical composition of a variety of mine tailings reported in the literature.

Mine type / Chemical Composition	Bauxite [63]	Boron [55]	Coal [64]	Copper [65]	Gold [39]	Iron [66]	Kaolin [29]	Graphite [49]	Phosphate [67]	Quartz [68]	Tungsten [51]	Vanadium [69]	Zinc [70]	Copper & Zinc [71]	Lead & Zinc[72] Silicate	Lead & Zinc[72] Carbonates
CaO (%)	3.15	14.36	1.06 -8.41	8.14	14.89	6.20	0.2	15.547	34.2	0.51	28.02	6.51	33.66	0.84	1.99	19.83
SiO_2 (%)	32.24	19.57	52.34 - 61.92	44.54	44.62	24.40	59.5	62.50	22.8	79.53	36.52	61.92	6.20	25.16	68.44	7.16
Al_2O_3 (%)	37.39	6.17	19.50 - 36.34	16.18	8.64	10.95	32.9	10.21	2.5	9.52	8.70	7.35	2.06	6.41	9.38	3.09
Fe_2O_3/ TFe (%)	8.67	2.85	6.42 - 8.35	-	26.1	31.15	2.7	5.07	0.9	3.22	11.71	4.12	0.19	19.24	2.22	2.11
SO_3/ S (%)	-	0.34	0.11 -0.65	5.14	2.31	-	0.1	-		-	0.16	7.14	1.46	26.18	1.12	7.51
MgO (%)	0.85	4.26	1.0 - 1.57	-	0.51	0.99	-	2.33	4.1	0.64	1.12	1.24	9.94	1.69	0.48	11.27
K_2O (%)	-	2.31	2.65 - 4.02	-	0.55	0.86	0.1	2.26	0.4	3.24	0.05	1.25	0.24	0.41	5.46	0.48
TiO_2 (%)	2.31	-	0.85 - 1.21	-	0.41	0.42	2.0	-	-	0.52	0.12	0.46	0.09	0.09	-	-
Na_2O (%)	0.85	0.18	0.17 - 0.53	-	1.63	0.28	-	-	0.8	0.72	-	2.66	0.30	0.23	0.7	0.1
MnO (%)	-	-	0.06 - 0.14	-	0.09	-	-	-	-	0.16	2.56	-		0.07		
Cl (%)	-	-		-	0.02		-	-	-	-	-	-		0.04		
ZnO/ Zn (%)	-	-	27 - 46 ppm	0.65	0.11	-	-	-	-	78.82 mg/kg	0.02	-	1.77	0.31	230 ppm	260 ppm
PbO/ Pb (%)	-	-	-	-	-	-	-	-	-	195.90 mg/kg	-	-	0.15	0.14	4710 ppm	5940 ppm
Cu (%)	-	-	-	-	-	-	-	-	-	75.24 mg/kg	-	-		0.19		
Cr_2O_3/ Cr (%)	-	-	-	-	-	-	-	-	-	-	0.03	-		0.02		
WO_3 (%)	-	-	-	-	-	-	-	-	-	-	0.03	-		-		
V_2O5/ V (%)	-	-	-	-	-	-	-	0.308	-	-	0.02	0.42		50.30 ppm		
SrO/ Sr (%)	-	0.51	-	-	-	-	-	-	-	-	-	-		21.40 ppm	1.12	7.51
BaO/ Ba (%)	-	-	-	-	-	-	-	-	-	-	-	-	0.31	0.008		
P_2O_5 (%)	-	-	-	-	-	-	0.4	-	-	-	-	-	0.27	0.04		
ZrO_2/ Zr (%)	-	-	-	-	-	-	0.1	-	-	-	-	-	0.003			
LOI (%)	13.74	21.06	1.81 - 5.61	18.92	-	6.95	2.0	0.65	19	2.46	2.30	6.93	43.35	18.68		
SiO_2/Al_2O_3	0.86	3.17	1.70-2.68	2.75	5.16	2.23	1.81	6.12	9.12		4.20	8.42	3.01	3.93	7.30	2.32
Basicity Modulus $\left(\frac{CaO+MgO}{SiO_2+Al_2O_3}\right)$	0.06	0.72	0.03-0.10	0.13	0.29	0.20	-	0.25	1.51		0.64	0.11	5.28	0.08	0.03	3.03
Hydraulicity Modulus $\left(\frac{CaO}{Fe_2O_3+SiO_2+Al_2O_3}\right)$	0.04	0.50	0.01-0.08	0.13	0.19	0.09	0.002	0.20	1.31	0.49	0.09	3.98	0.02	0.02	1.60	0.04

*The chemical compositions reported in the table are indicative for a particular type of tailing observed in a study and does not represent a mean or median.

** All values given in the table are in percentage unless otherwise specified.

289   **Table 2:** Mineral composition of a variety of mine tailings (Note: The percentage composition
290   of minerals is reported only in a few studies).

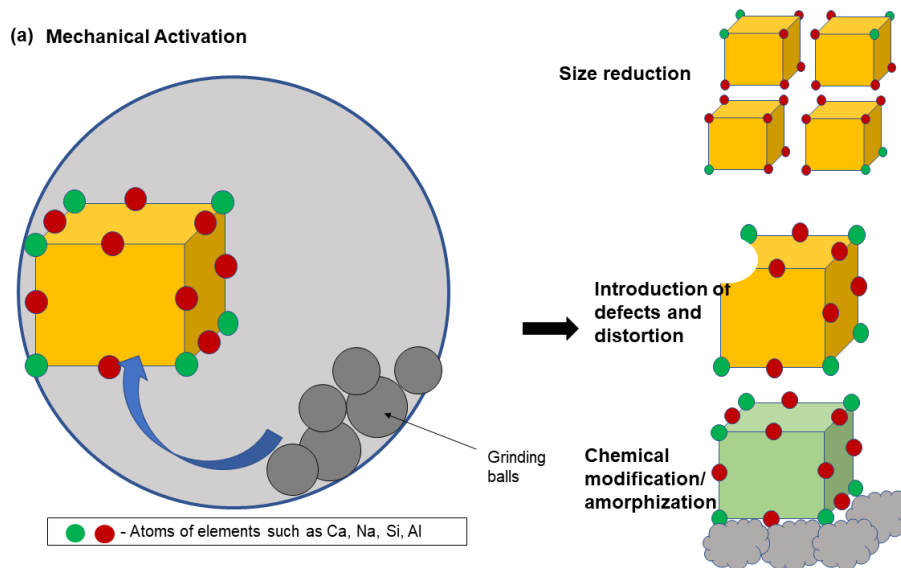| Sl. No	Mineral waste	Mineral	% Composition	Sl. No	Mineral waste	Mineral	% Composition
1	Bauxite [63]	Kaolinite				Hematite	1.07
		Diaspore				Other	4.03
		Muscovite					
		Anatase		7	Low sulphide Lead - Zinc [48] Carbonate dominant (80%)	Dolomite	
		Corundum				Calcite	
		Quartz				Ankerite	
		Mullite				Barite	
2	Boron [55]	Hydroboracite				Kaolinite	
		Montmorillonite				Smithstone	
		Colemanite		8	Kaolin [73]	Kaolinite	
		Illite				Mica	
		Quartz				Quartz	
		Calcite		9	Phosphate [74] [57,75]	Quartz	0.9 – 12.44
3	Coal [76,77]	Quartz	29 – 37			Apatite	9.6
		Mica	25			Fluorapatite	34.09 - 44
		Calcite	15 – 17			Calcite	11.15
		Kaolinite	14 – 15			Dolomite	9.45 – 89.5
		Dolomite	5			Illite	9.46
		Feldspar	2			Palyrgorskite	21
		Amorphous	17			Hematite	1.4
4	Copper [65,78–80]	Albite		10	Tungsten [51,81]	Garnet	88.14
		Gypsum				Amphibole	5.46
		Sanidine				Chlorite	4.27
		Quartz				Quartz	2.13
		Augite				Muscovite	
		Dolomite		11	Vanadium [82]	Quartz	
		Phlogopite				Feldspar	
		Amphibole				Diopside	
		Clinochrysotile		12	Low sulphide Lead - Zinc [48] Silicate dominant (90% silicate)	Quartz	
		Calcite				Orthoclase	
		Talc				Chlorite	
		Clinochlore				Albite	
		Siderite				Barite	
		Hematite				Fluorite	
		Pyrite		13	Desulphurized pyrrhotite tailings [26,83]	Magnetite	2.56
		Mullite				Orthoclase	1.37
		Muscovite				Pentlandite	0.29
5	Gold [39,50,84]	Albite				Pyrrhotite	0.64
		Gypsum				Quartz	1.60
		Quartz				Rutile	0.30
		Dolomite				Actinolite	29.75
		Muscovite				Albite	2.76
		Microcline				Arsenopyrite	0.01
		Pyrite				Calcite	2.17
		Sodium aluminium silicate				Chalco Pyrite	0.25
		Sanidine				Clinochlore	26.48
		Mica				Lizardite	31.81
		Montmorillonite		14	High sulphide tailings Copper and Zinc [71,85]	Pyrite FeS_2	
6	Graphite [59]	Quartz	43.15			Anhydrite $CaSO_4$	
		K-Feldspar	12.42			Caldecahydrite $CaAl_2O_4$ $10.H_2O$	
		Albite	5.08			Quartz SiO_2	
		Anorthite	3.31			Smithstone	
		Biotite	8.34			Diopside	
		Muscovite	4.82			Calcite	
		Epidote	2.05			Albite	
		Chlorite	3.13			Sodium copper sulfide	
		Rutile	0.72				

291

3.3 Activation Processes

The structural stability of any material is associated with its chemical reactivity. Materials with
more defects in their microstructure, more distortion in their lattices, or materials existing in an
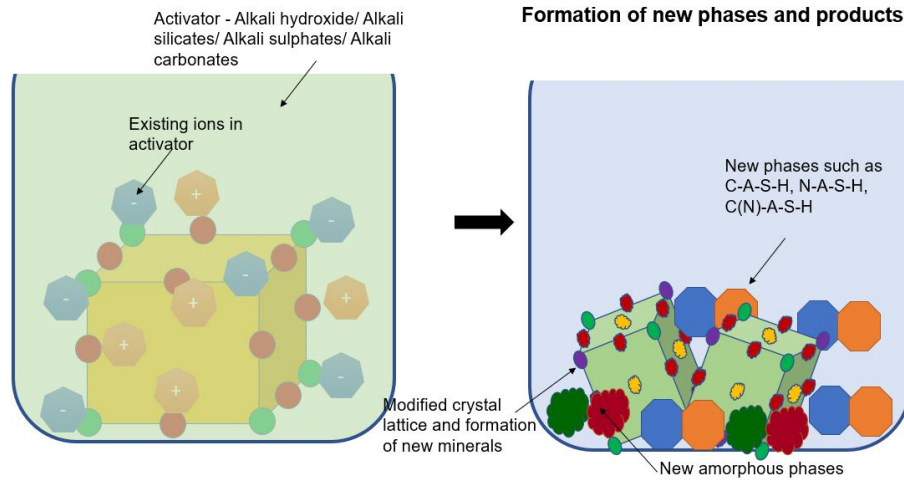
295   amorphous state are considered to have less stability and tend to have a high reaction activity
296   [86]. Since mineral wastes, and hence tailings, are highly crystalline their processing is
297   essential to render them more reactive for use in cementitious systems as part of the binder
298   phase. This processing is commonly known as "activation". Activation processes can be either
299   mechanical, chemical, thermal or a combination of them (see Fig. 3). For use in cementitious
300   matrices, the mine tailings can be alumino-silicate, calcium-alumino-silicate or predominantly
301   silicate. The energy required in the processing of tailings should be of sufficient magnitude to
302   rearrange the crystalline lattice. For example, in case of an alumino-silicate mineral if the
303   binding energies of the Al-O-Si, Si-O-Si or other structural forms present in the raw material
304   are strong, energy higher than binding energy may be required to disrupt the bonds in
305   crystalline lattice and make ions available for further reaction [87]. The thermal activation is
306   achieved by calcination of the material in a high temperature furnace. The mechanical
307   activation can be performed by means of ball mill, ring mill, planetary ball mill, vibratory ball
308   mill, stirred ball mill or jet mill [88,89]. The chemical activation is achieved by use of an activator
309   to induce chemical reactions for release of Si, Al and other ions and enabling further reactions.
310   When alkalis are used for this purpose, the process is known as alkali activation [90]. The
311   following sections discuss the various activation processes found in the literature. Table A1 in
312   the Appendix provides detailed information about the application of activation processes for
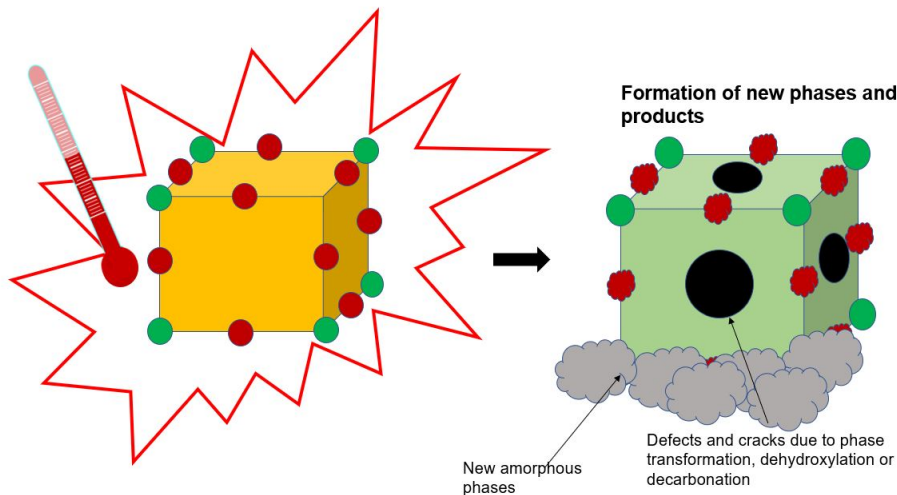313   individual minerals as reported in published research.

(a) Mechanical Activation

Size reduction

Introduction of defects and distortion

Chemical modification/ amorphization

Grinding balls

● ● - Atoms of elements such as Ca, Na, Si, Al

314

(b) Chemical Activation

Activator - Alkali hydroxide/ Alkali silicates/ Alkali sulphates/ Alkali carbonates

Existing ions in activator

Formation of new phases and products

New phases such as C-A-S-H, N-A-S-H, C(N)-A-S-H

Modified crystal lattice and formation of new minerals

New amorphous phases

315

(c) Thermal Activation

Formation of new phases and products

Defects and cracks due to phase transformation, dehydroxylation or decarbonation

New amorphous phases

316

317 **Fig.3:** Schematic representation of the mineral activation processes: (a) Mechanical; (b) Chemical and
318 (c) Thermal activation.

319

320 <u>3.3.1 Calcination or Thermal treatment</u>

321 As the formation of crystalline phases in the minerals is a function of temperature, calcination
322 is known to impart changes in the crystal structure of the minerals. The general modifications
323 which happen during the calcination are:

324

325 (i) ***dehydroxylation*** of hydroxides in minerals such as kaolinite at about 580 °C and mica at
326 about 700 °C [73]

327

328 and (ii) ***decarbonation*** in carbonate minerals such as calcite, dolomite, siderite smithsonite
329 etc [48,91]

330

331 The dehydroxylation of phyllosilicate minerals improves the reactivity as the loss of hydroxides
332 generates more disorder and exposure of Al ions favouring their dissolution. [92]. Therefore,
333 this method of activation has been found suitable for mine waste containing a large amount of

12

phyllosilicate or carbonate minerals. However, minerals such as albite though they exhibit dehydroxylation at a higher temperature do not exhibit any change in crystal structure [93]. The calcination also involves alpha – beta transformation of quartz. Such transformations are generally accompanied by increase in volume and hence lead to formation of cracks thus further improving the reactivity by exposing new surfaces available for reaction [94]. Past studies show that minerals such as albite [93], apatite [54], arsenopyrite [95], calcite [64], chlorite [96], clinochlore [97,98], corundum [99], diaspore [63], dolomite [96], feldspar [100], hematite [101,102], hydroboracite [55], montmorillonite [92], talc [103], undergo modifications when calcined at temperatures between 540 °C and 1450 °C. Therefore, thermal treatment shall be effective for mine tailings with these minerals as major phases.

The choice of treatment temperature also depends on the minerals present in the mine tailings in their raw form. Torgal and Jalali reported that calcination of mine tailings at 750 °C had no effect on the compressive strength of the cementitious matrix containing them. However, further increase of the calcination temperature to 950 °C resulted in an increase in the compressive strength values due to formation of amorphous products [104]. Beyond 950 °C, thermal treatment resulted in the formation of crystalline phases crystalline phases, such as mullite, which reduced the reactivity and hence did not yield an improvement in the measured mechanical properties.

Calcination in presence of alkali or alkaline roasting or thermo chemical activation
Calcination of tungsten mine waste in presence of sodium carbonate yielded a maximum strength at a calcination temperature of 500 °C instead of 950 °C [104]. Minerals such as albite when calcined in presence of NaOH or Na_2CO_3 they completely shift to an amorphous state due to loss of crystalline ordering of Al and Si [93]. Similarly, calcination of mine tailing in presence of alkalis at 600 °C indicated decrease in crystalline silica and albite and formation of biotite. Also, it is important to take into account the disintegration temperature of activator during alkaline roasting, or else the disintegrated compounds may lead to leaching or formation of efflorescence during hydration [104]. Kaze et al [105] in their study reported that the presence of high amounts of iron (almost 50%) led to a structural disorder in clay minerals where Al ions are replaced by Fe ions. These inherent defects result in reduction in crystallinity and requires lower thermal activation energy.

3.3.2 Mechanical and Mechano-chemical Activation
Mechanical activation utilises mechanical actions to induce changes on the microstructure of minerals. Mechanical processing essentially decreases the particle size and increases the surface area of the materials. This in turn improves the reactivity [50]. The most commonly used mechanical activation is grinding which involves a combination of pressure and shearing actions on the material. Research indicates that grinding improves reactivity of tailings by dynamic creation of new surfaces, by creating defects in crystal lattice and phase transformations. [50,69,86,89]. It was also reported that during grinding due to friction and impact of the grinding media on the material a localised increase in temperature may be observed in a small area leading to mechanically activated chemical reactions [89]. The electron energy at such localised contact points is about 10 eV which is higher than energy of thermal treatment at 1000°C (4 eV) [88]. The variation in specific surface area of different tailings with respect to grinding time is given in Fig. 4. A phenomenon called selective grinding occurs when minerals of high and low hardness are present in the same material and the minerals with higher hardness act as a grinding media for minerals of lower hardness and

accelerate the grinding process [51,89]. Minerals of high hardness such as garnet and quartz have a particle size larger than other minerals after grinding of the mine waste. A bimodal particle size distribution curve after grinding represents the presence of minerals with different relative grind ability present in the same material [51]. This property of different minerals being downsized by different extent for the same amount of grinding energy applied is called grinding performance or grindability. And better grinding performance is crucial for economic and environmental efficiency [106].
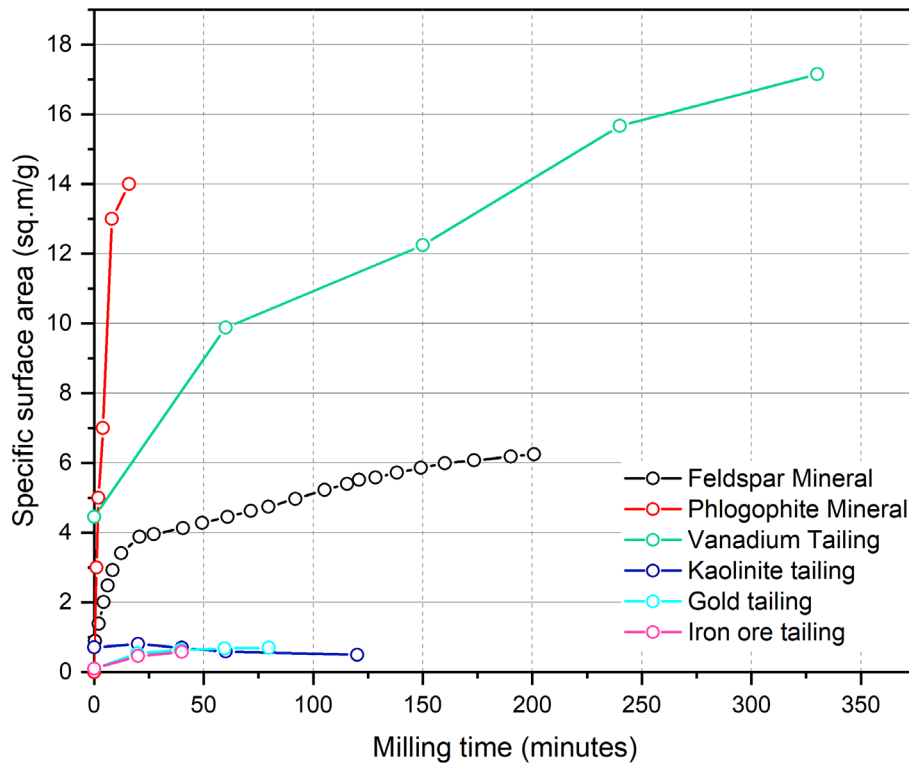
Fig. 4: The specific surface area of tailings with respect to grinding time [50,69,107–110].

In certain cases, grinding also breaks the Al-O-Si, Si-O-Si bonds further improving the reactivity of minerals. A recent study has shown that the content of reactive Si and Al increased from 300 to 1500 mg/ L and from 100 to 315 mg/ L respectively after 5.5 hours of grinding [69]. Similarly, Yu et al. [35] reported an increase in reactive Si and Al content by 26.03% and 96.33% respectively, after 4 hours of grinding. Grinding beyond 3 h leads to increased surface energy which in turn results in agglomeration of particles. Therefore, an increase in the particle size is observed after 3 h of grinding in case of copper tailings and 4 hours grinding in case of iron tailings [35,111]. This phenomenon was explained by Tole et al [89] as given in Fig 5.
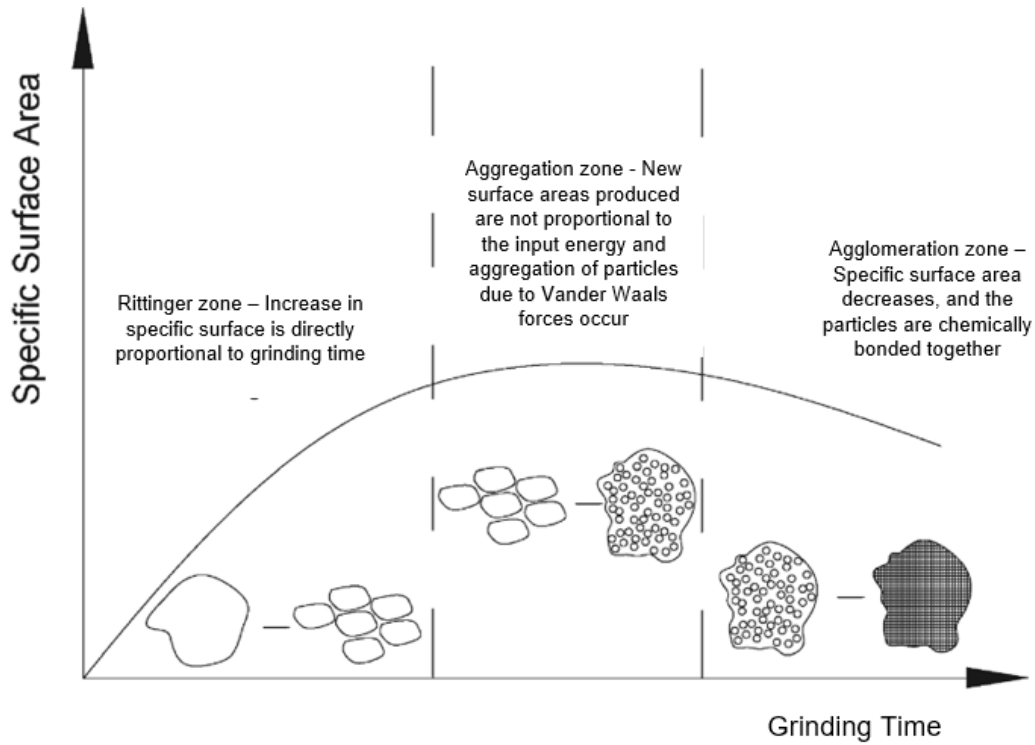
Fig. 5: Reaction evolution of particles during mechanochemical activation. Image reproduced from [89].

The XRD analysis showed that intensity of quartz, endenite, albite, hematite and feldspar peaks were significantly decreased after 4-5 hours of grinding [35,111]. After melting, quenching and grinding the reactivity of phlogopite increased from 1% to 40% [54]. Yao et al [50] reported that the relative crystallinity of muscovite reduced to 37% whereas the crystallinity of quartz reduced only to 80% after 80 minutes of grinding. Clinochlore exhibited a complete collapse of mineral structure after 16 minutes of milling [112]. The increase in amorphous content of different mine tailings and minerals with grinding is given in Fig. 6 while in the literature researchers have also used TEM (see Fig. 7) to confirm the formation of amorphous phases pre- and post- mechanical treatment.

15
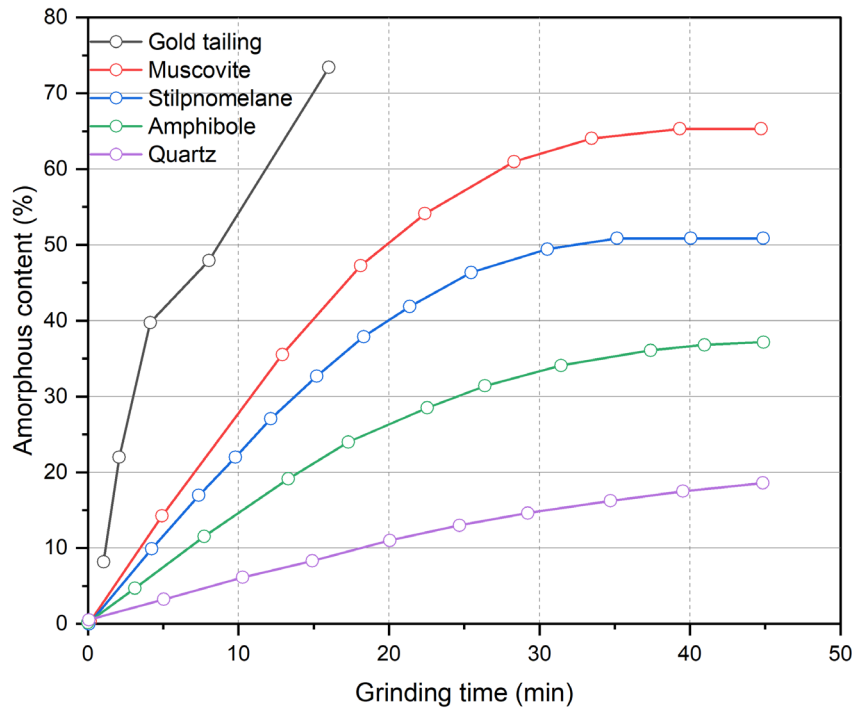
Fig. 6: Amorphous content of different tailings and minerals with respect to grinding time

Fig. 7: TEM images of kaolinite-talc mixture: (a) before and (b) after grinding. The well-developed pseudo hexagonal crystals were converted to shapeless amorphous materials after 60 minutes of grinding. Image reproduced from [108] with permission from Elsevier.

3.3.3 Chemical Activation

Alkali activation of mine tailings refers to the use of alkalis to stimulate the potential activity by dissolution. It is not to be confused though with the term "alkali activation" that refers to alternative to cement binders, in some cases known as "geopolymers". In both cases, the alkalis used for this purpose are known as activators. In tailings treatment, the most widely used activators are MOH, M_2SiO_3, M_2SO_4 and M_2CO_3 where M refers to either sodium or potassium [53]. The dissolution of silica and alumina from the source material is generally dependant on: (i) the strength Si-O-Al bonds; (ii) the formation of soluble species from the source; (iii) the pH of the solvent medium (i.e. activators) and (iv) the temperature of the system in which reaction takes place [16,113]. Studies showed that the time and rate of release of Al and Si ions play a crucial role in strength gain. Though the rate of dissolution of Si can be increased with increased alkali concentrations, the concentration of Si, Al, Ca in the binder, the glass content and the fineness of the precursor, played the most important role in strength gain [16,113]. Most studies therefore used alkali activation in combination with other activation methods such as grinding and calcination to attain the optimum conditions [29,55,112].

When it comes to geopolymerisation, it was found that grinding improved the rate of reaction due to increase in the specific surface area [69]. Xu and Deventer [114] suggested that alkali activation can be performed both on calcined and non-calcined materials, and calcined materials had better reactivity due to their more amorphous nature. Their study also reported that geopolymerisation of multiple minerals combined is possible, showing alkali activation can be suitably applied for mine tailings. Torgal et al [115] observed that the compressive strength increased with increase in molarity of the activator while past studies indicate that the better strength was achieved when the SiO_2/Al_2O_3 ratio of the system (precursor + activator) ranged between 3.0 – 3.8 [116]. Liew et al [117] found that the optimum SiO_2/Al_2O_3, SiO_2/Na_2O, Al_2O3/Na_2O and H_2O/Na_2O molar ratios were 3.10, 2.69, 0.87 and 14.23 respectively, for calcined phyllosilicate minerals whereas Xu and Deventer [62] observed a higher compressive strength for alkali feldspar minerals when the Si/Al ratio was maintained between 2.21 – 2.38.

In general, when the precursor's Si/Al ratio value does not fall within the above-mentioned range, an additional source of silica as sodium silicate activator and/or alumina are added. The most commonly added materials are metakaolin, ground granulated blast furnace slag, fly ash, milled glass waste, [67,70,71,118,119]. Kiventera et al [119] adopted Si/Al value less than 3, between 1.5 - 2.5 and Na/Al ratio in the range of 1.0 – 1.29, to proportion a mixture of fly ash, ground granulated blast furnace slag and gold mine tailing. The mix was found to have better strength and microstructure when metakaolin was added and the Si/Al was 2.5 and Na/Al was 1.0. Peng et al., [51] activated tailing rich in garnet and quartz, using $Ca(OH)_2$, gypsum and sodium silicate as different activators and found that the reactivity of mine tailings improved by 67.65%, 27.73% and 36.29 % respectively. Others have used NaOH in presence of fly ash and metakaolin to activate calcined tailings comprising calcite, quartz, dolomite and mullite [67]. When fly ash was used quartz, dolomite, calcite, mullite, hydro-sodalite, chabazite were present in the activated paste whereas the use of metakaolin led to the formation of quartz, dolomite, calcite, hydro-sodalite and sodium aluminium silicate [67]. The presence of dolomite, calcite and quartz phases before and after activation indicated that they were unaffected by alkali activation [67]. However, the interlocking of unreacted large particles contributed to strength development after hardening [51]. Jiao et al. [82] activated ground tailing using Na_2SiO_3 and found Si/Al = 3.3, Na/Al = 1.0 and H_2O/Na = 1.6 were optimum for

activation. The studies with both sodium and potassium activators indicated that a geopolymer paste with highly reactive precursor when used with a low viscous activator such as KOH or K_2SiO_3 exhibits cracks due to accelerated evaporation of water which otherwise would have been available for geopolymerisation [87]. Koohestani et al [85] reported a formation of silica gel when the pH of the system was 8.7. Evidence in the literature suggests that high calcium content in the mine tailings can turn the tailing itself to an activator [30]. Furthermore, mine tailings can be used as an inert filler in geopolymers in presence of a co-binder [47]. In case of alkali activation of minerals rich in Fe [105,120], it was observed that Al^{3+} ions were replaced by Fe^{3+}. This resulted in formation of Si-O-Fe linkages and hence Fe^{3+} binders are formed. Peys et al [120], from their study reported that the synthesis of this phase is observed when the Na/Fe^{3+} is almost equal to 1 and Si/Fe^{3+} is almost equal to 3. The study also reported that the Fe^{2+} ions after dissolution is oxidised to Fe^{3+} during or after the synthesis of geopolymer.

The major advantage of alkali activation of mine tailing is that, unlike the other two methods of activation, alkali activated mine tailings can be used as a standalone cement. Alkali activation also: (i) helps in encapsulation of heavy metals and metalloids and thus prevents its leaching; (ii) it has low energy consumption demand and (iii) has better acid resistance [119,121]. Mine tailing alkali activation can be considered akin to engineering the same waste to cater different needs by modifying the activators, e.g. tungsten mine waste when activated with NaOH and $Ca(OH)_2$ exhibited optimum mechanical properties with shrinkage less than OPC whereas when activated with Na_2CO_3 had high early age strength but performed poorly under water [122]. However, the disadvantage in using mine tailings is the effect of presence of Cu^{2+}, Fe^{2+}, Fe^{3+} in the formation of geopolymer chains, which is still not well established. Also, the alkali activation may form hydration products which are unstable thus the binder exhibits high early strength and decrease in strength at later ages [104].
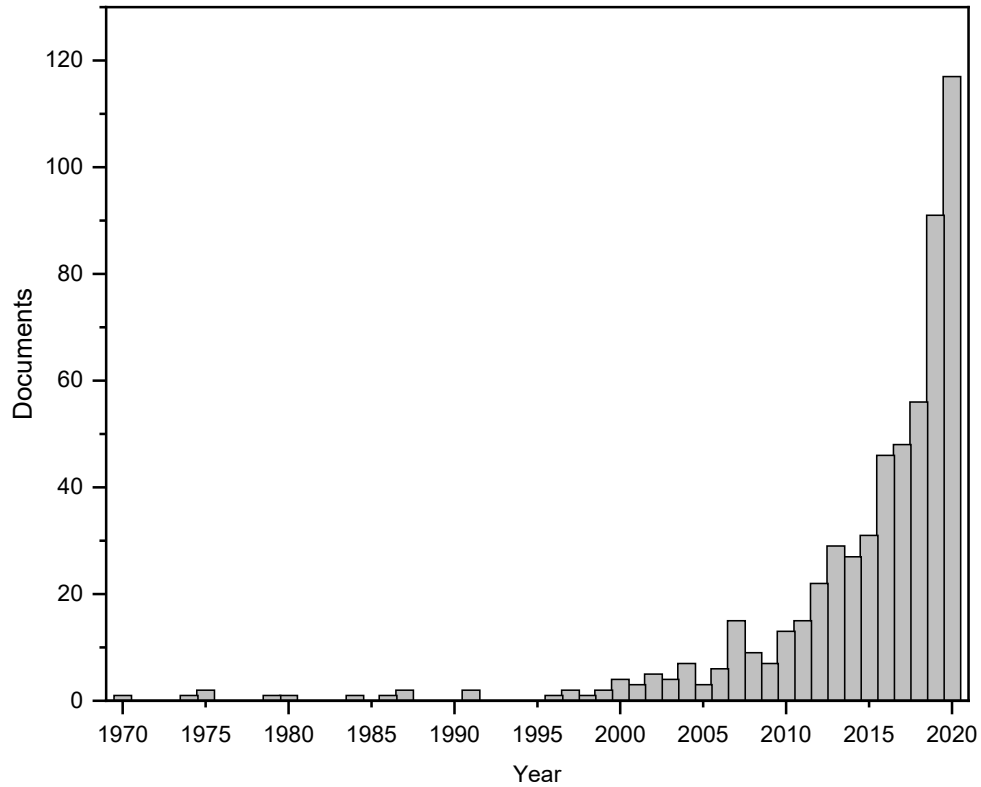
4. Mine Tailings in Cementitious Binders

The use of mine tailings in construction related applications gradually gains a lot of interest. These applications range from backfilling to the use of tailings as part of a binder. The growing interest in the area is reflected by the continuously growing number of studies published (Fig. 8). The utilisation of tailings as part of the binder in particular has significantly increased the last decade (between years 2012-2021) with a growing number of studies reporting various percentages incorporated (Fig. 9). It is interesting to note that a very wide spectrum of % replacement is covered ranging from as low as 5% to as much as 100%.

Fig. 8: Number of studies discussing the use of mine tailings in construction related applications (data obtained by Scopus).
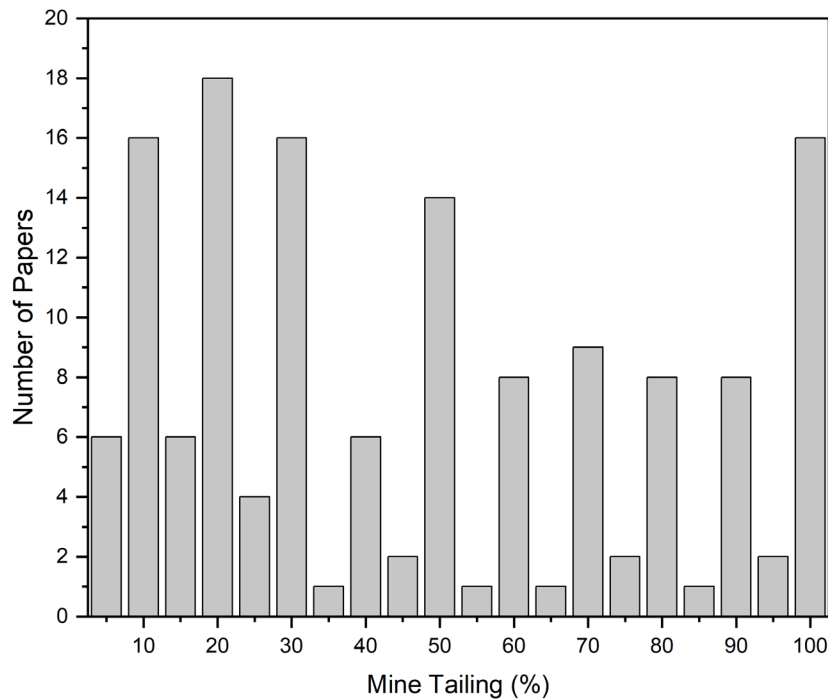
Fig. 9: Number of studies reporting the utilisation of various % of mine tailings in cementitious binder.

4.1 Mineralogy and Microstructure

Understanding the mineralogy and microstructure of binders containing mine tailings is very important towards properly understanding their behaviour. The studies found in the literature

are still limited but some useful initial conclusions have been drawn already. Generally, the microstructure and mineralogy of the binders containing mine tailings were affected by various factors including the percentages of tailings, type of usage (as admixture, SCM or cement replacement), water content, activator, and presence of mineral admixtures.

4.1.1 Alkali Activated Binders

In geopolymers with alkali activated calcined Kaolin mine tailings, poorly crystalline pseudo zeolitic alumino silicate gel, anatase and kaolinite were observed when SiO_2/Al_2O_3 ratio was high (sodium silicate activator). However, in systems activated only with NaOH, the crystalline products of hydrosodalite and Trona were identified [29]. Sedira et al. [98] activated tungsten mine waste with brick waste using NaOH and Na_2SiO_3. Poorly formed K-A-S-H, C-A-S-H, N-A-S-H gels were observed indicating alkaline activation of the products was not complete. Samples with more brick waste had lesser pore diameter and pore volume than the mixes with mine waste alone. Similar observation was made with the use of GGBFS, where the unreacted particles of the mine tailing and slag found to be surrounded by newly formed reaction products [123]. An area of concern is that mixes with mine tailings can potentially lead to matrices with increased porosity [124]. Silva et al [125] reported that when alkali activated, chamosite is converted to crystalline phase zeolite type (sodalite). With use of sodium silicate activators, minerals such as gypsum, quartz, sodium aluminium silicate, magnesium sulphate, magnesite, pyrite were formed in the alkali activated paste whereas sodium aluminium silicate, quartz, magnesium sulphate, pyrite, akermanite, magnesite were present in the raw tailing. Sedira et al [123] reported that mixes with sodium silicate and sodium hydroxide exhibited more cracks due to higher shrinkage when compared to mixes with sodium hydroxide only. Also, the mixes with higher solid to liquid ratio had a more cohesive microstructure. Wang et al [126] in their study with garnet tailings showed that on third day as given in Fig 10(a), the matrix appeared as if many particles of 2-5 μm are glued together. This can be attributed to the high crystallinity of the raw material. However, at later ages (7 days and 28 days) it the original large sized particles present formed a three-dimensional crosslinked structure. Fig. 10 (d-f) show that the initial dissolution of the particle has been accelerated by the presence of metakaolin (20%) in the system. It is evident from the absence of large sized particle in Fig. (d) of geopolymer paste made of garnet tailing with metakaolin captured at 3 days.

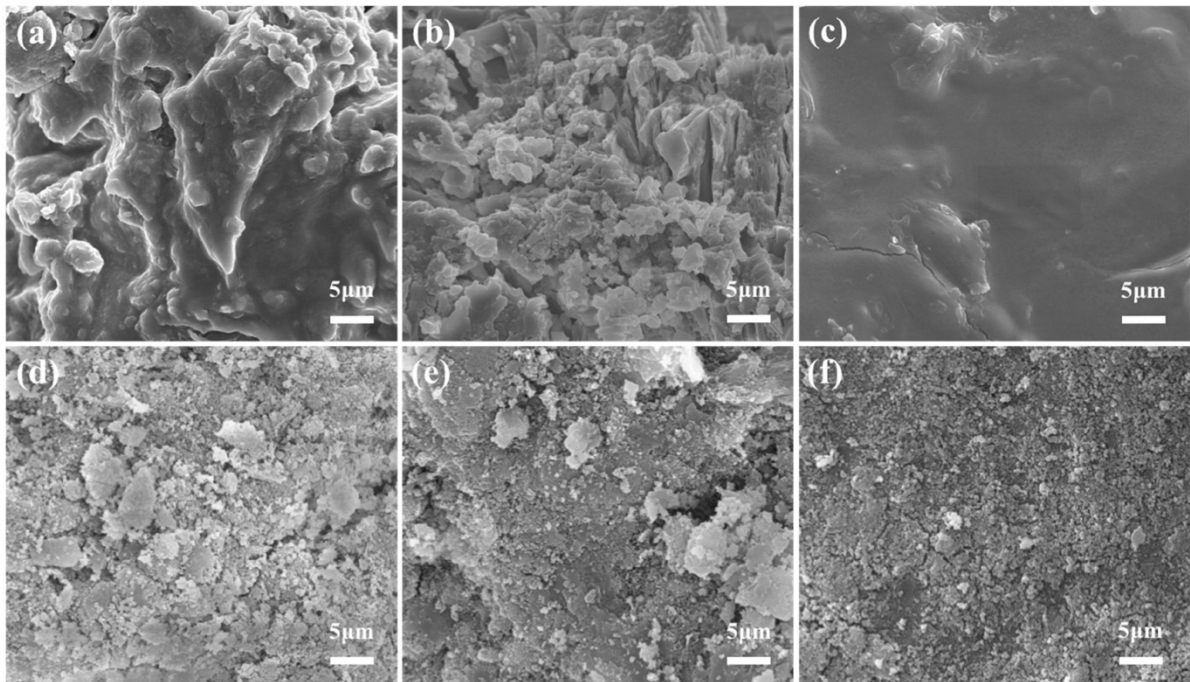**Fig. 10**: Microstructure of garnet mine tailing based geopolymer at 3, 7 and 28 days (Image reproduced from Wang et al [125]).

4.1.2 Portland Cement Replacement and Supplementary Cementitious Material

In the literature, one can find several combinations of how mine tailings are incorporated in cementitious matrices. Mixes with tailings, lime powder (10%) and OPC indicated the formation of quartz, calcite, dolomite, pyrite, siderite, muscovite, clinochlore, hematite and ettringite [65]. Phases such as portlandite, quartzite, alite, quartz, ettringite, calcium ferric aluminate hydrate, albite and epidote were found in mixes with 20% mine tailings and OPC. This indicates that all phases in mineral tailings cannot be consumed by hydration [127]. Martinez et al. reported that total porosity increased by 28% and mean pore size decreased by 42% with 50% replacement of OPC by activated coal mine waste [76]. Ince [39] reported both reduction in pore size and pore volume with increase in percentage of mine tailing. The study reported that the porosity decreased from 37.5 % to 32 % for 30% cement replacement. Cheng et al [86] reported that mixes with mine tailing had a flocculent structure in their calcium silicate hydrates (C-S-H) accompanied by lesser quantity of portlandite crystals and attributed this to the lower Ca/Si value. However, the overall microstructure was more compact and uniform. A similar observation was made by Liu et al [128] in samples of 90 days age, whereas at 3 days it was seen that the Ca/Si value was high due to faster dissolution of Ca from the cementitious system than Si from the mine tailings. This gradually reduces with age and hydration and resulting in secondary reactions leading to formation of flocculant C-S-H as seen in Fig. 11.
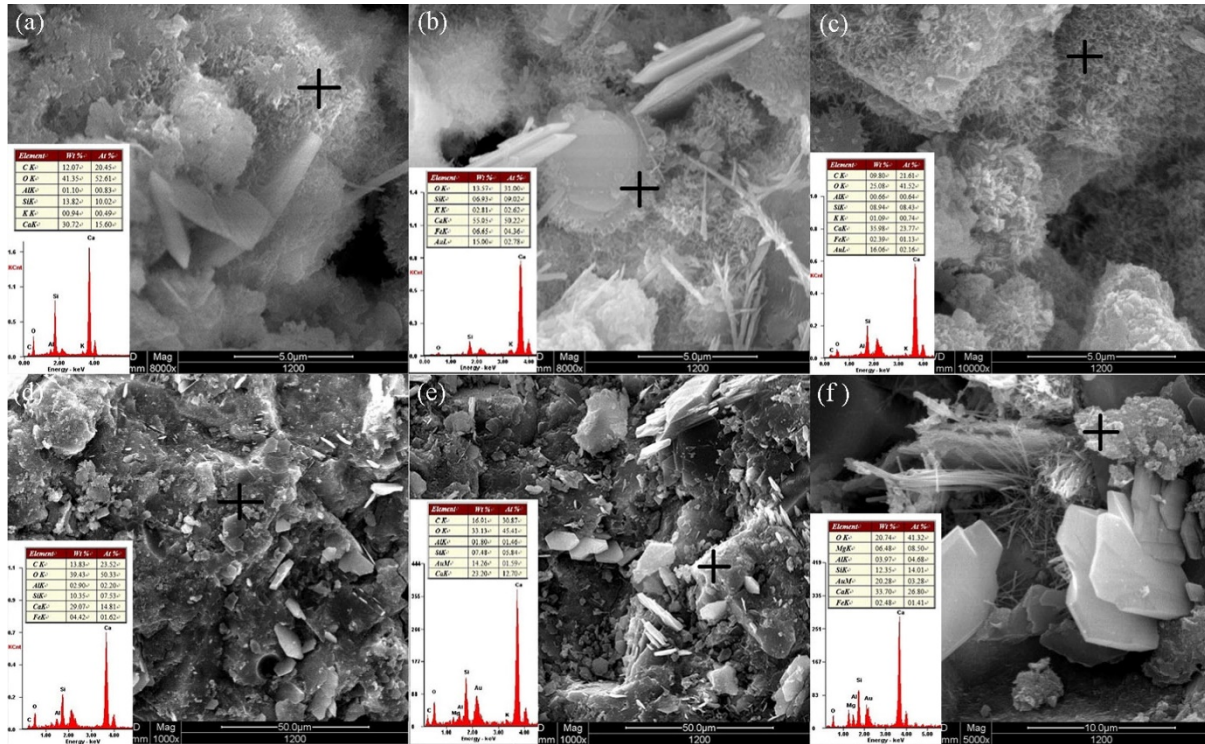
21

Fig. 11: Microstructure of cement paste with 0, 15, 45 % mine tailing at ages 3 (a-c) and 90 (e -f) respectively (Image reproduced from Liu et al [128]).

4.2 Hydration and Fresh Properties

Early age properties are rather critical for any binder. Fresh properties define placement and handling whereas hydration kinetics affect setting times and hence have a knock-on effect on the evolution of properties. It is well known fact in concrete technology that the addition of powdered additions has an impact on early age properties. While the published data on traditional SCMs is quite rich and conclusive, for mine tailings it is still early days. The available research is very limited and far from conclusive.

4.2.1 Alkali Activated Binders

Rao and Liu [129] reported workability as a function of alkali concentration and reported mixes made with activator at pH 14 had better workability than activator at pH 12, whereas Kiventera et al., [130] reported that the workability decreased with increase in concentration of alkalis in case of the highly sulphidic mine tailing. Perumal et al., [131] reported that the setting behaviour of alkali activated mine tailing was mainly dependant on the minerals present in it for the same activators used. Koohestani et al [85] reported that increase in sodium silicate delayed the setting of pastes. While it can be comprehended that the workability of the mine tailing is a function of minerals present and the concentration of activator, it can be seen clearly from Fig. 10 that the crystallinity of the mine tailing had an impact on hydration and the matrix formation of the pastes after alkali activation. The mechanism of polymer formation involves the following steps: i) dissolution; ii) poly-condensation; iii) gelation and iv) hardening [53,61,85,87]. This mechanism is summarised for mine tailing in Fig. 12.
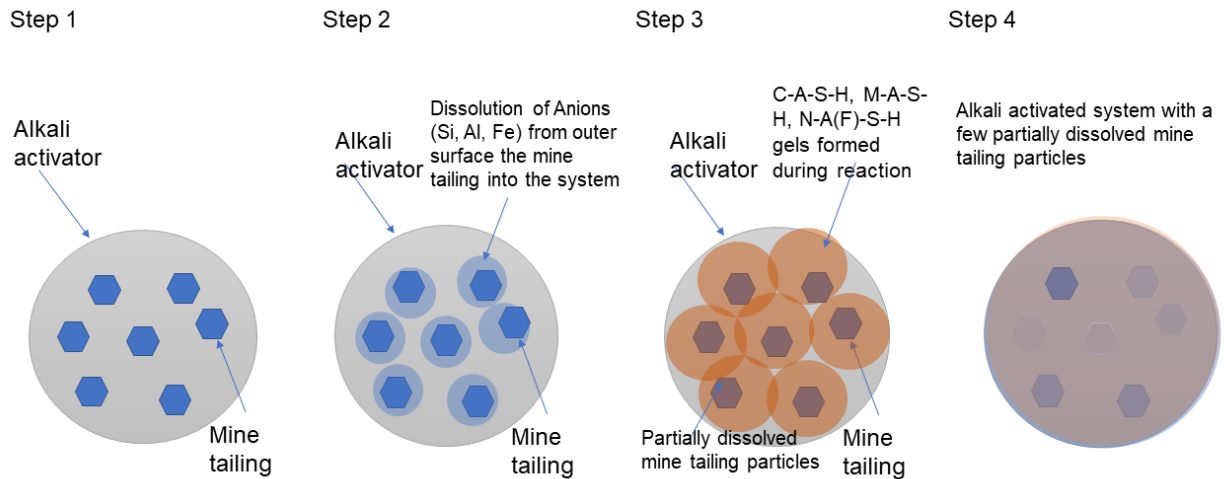
22

Fig. 12: Mechanism of alkali activation of mine tailing: Step 1: dissolution; Step 2: poly-condensation; Step-3: gelation and Step 4: hardening.

4.2.2 Portland Cement Replacement and Supplementary Cementitious Material

The general trend observed in the published studies is that increasing mine tailings addition in cementitious binders increases the water demand [33,36,39,71]. The addition of coal mine tailing as a raw material for clinkering increased the setting time due to its high lead (Pb) content [132]. The replacement of cement tailing by 30% phosphate mine waste led to an increase in setting time, bleeding and delayed the induction phase of hydration. The study confirms the use of phosphate tailing as direct cement replacement not only has a dilution effect but also a retarding effect due to dissolution of phosphate. Increasing the proportion of phosphate tailings led to a significant drop in the yield stress, plastic viscosity, and an increase in the thixotropy of the mix [74]. Other studies do not show significant effect on setting times with 10% addition having no effect on initial setting time whereas 20% addition increasing the setting time only marginally [64]. Ince et al [33] reported that the increase in quantity of mine tailing replacement from 0% to 20% led to decrease in setting time in both lime mortar from 1250 minutes to 1180 minutes and cement based mortar from 280 minutes to 220 minutes. The yield stress and plastic viscosity of the mortar decreased with increase in percentage of mine tailing replacement, and were found to be 30.4% and 35.8% lesser than control concrete for a replacement percentage of 30% [127]. Of course, the rheological effects depend on the fineness and reactivity of mine tailings and therefore more detailed and extended research is needed. There is also some early evidence that heat of hydration and induction period are also affected. Liu et al showed that the addition of mine tailings resulted in dilution of calcium ions in the cementitious system and hence delayed the saturation point and further strength gain [128]. Therefore, it can be considered that in the initial days of hydration, mine tailings act only as fillers. To summarise, the presence of mine tailing provides additional Si required for the pozzolanic reaction and facilitate the production of secondary C-S-H. However, this Si is available at a much later age due to slow reactivity of the mine tailing and sometimes leads to formation of C-S-H with a low Ca/Si ratio resulting in a low dense C-S-H. Therefore, to achieve binder of better mechanical performance it is imperative to adjust the percentage replacement or improve the reactivity of mine tailing to facilitate the additional Si is available at the right time and quantity for reaction. Also, the presence Cu^{2+}, PO_4^{3-} and impurities such as oil from production process affect the strength gain.

4.2.3 Filler

636 Using tailings as fillers, Siddique et al reported that with increase in mine tailing the flow of
637 mortar decreased even for the same water to binder ratio [133]. Similarly, Onuaguluchi and
638 Eren [36] found that flow decreased with increase in percentage of mine tailing and Zheng et
639 al [74] reported that the addition of mine tailing of a particle size higher than cement led to
640 lesser total surface area and hence reducing the water demand. The study also reported a
641 delayed setting time due to release of phosphorous ions which acts as retarder into the
642 hydrating system. Studies reported that as a filler the mine tailings increased the water
643 demand due to its higher surface area which in turn could delay the hydration and setting.
644 Also, as mine tailings might act as a reactive filler, it is important to consider its influence both
645 in packing density as well as chemical reaction.
646

647 *4.3 Mechanical Properties*
648 Studies on mortars containing mine tailings have shown compressive strength up to 75 MPa
649 as given in Table 3 and the relative compressive and flexural strengths are given in Fig 13 and
650 14. From all existing data it is evident that there is no generic trend of increase or decrease in
651 strength with the increase in percentage of mine tailings. The absence of specific patterns
652 can be attributed on various factors including particle size, type of cementitious binder, curing
653 temperature, type and extent of activation and the limited number of studies currently existing.
654 However, a point of convergence between studies is that 20-30% replacement appears to be
655 an optimum value so far.
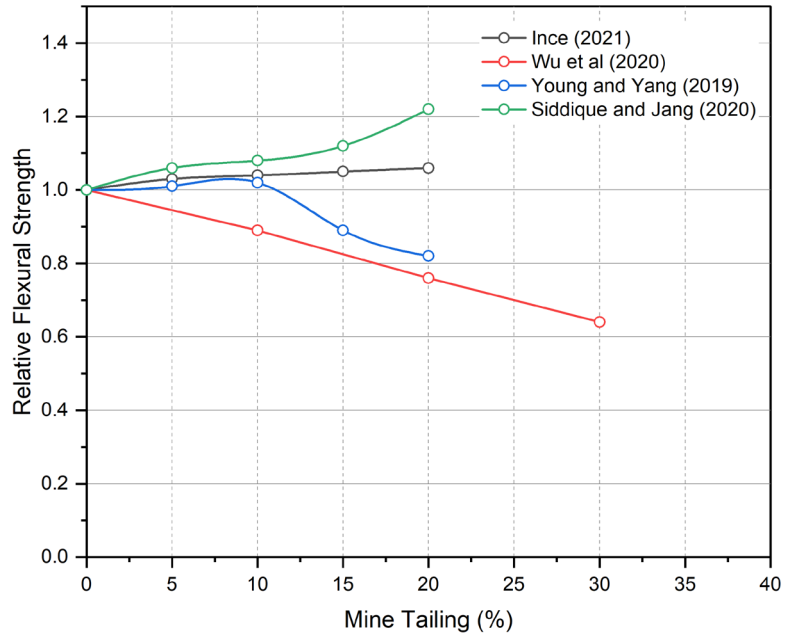656
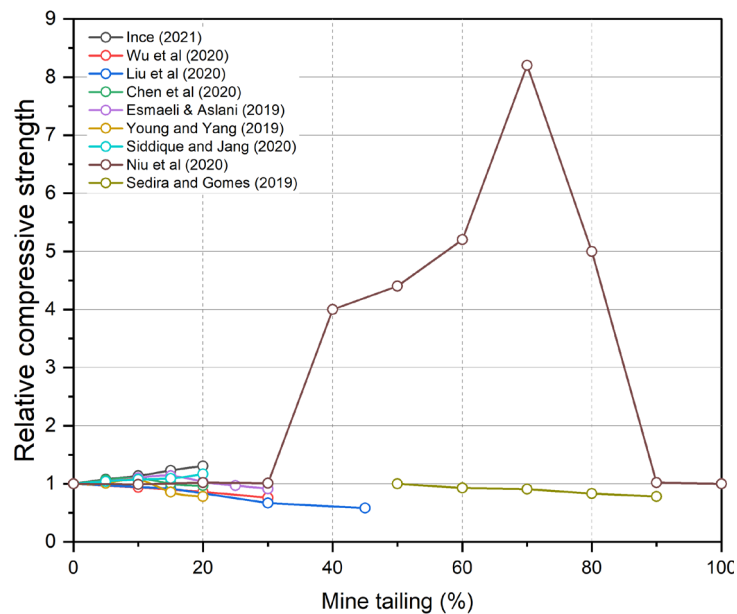
659 **Fig. 13**: Variation in compressive strength of samples with different percentages of mine tailings.
660

661
662   **Fig. 14:** Variation in flexural strength of samples with different percentages of mine tailings.
663

664 **Table 3: Compressive strength variation observed in various studies**

As cement replacement and supplementary cementitious material									
Sl. No	Type of tailing	Mix	Admixture	w/b ratio	Activation Process	Percentage replacement	Max. Compressive strength (MPa)	Variation in compressive strength compared to control concrete (%)	Study
1	Gold	Mortar	-	0.62	-	30% as cement replacement	37	13.9	[39]
2	Copper	Mortar	-	0.485	Mechanical activation	10% as cement replacement	46.5	35.5	[36]
3	Coal	Mortar	-	0.50	Thermo mechanical activation	10% as cement replacement	64	- 8.3	[64]
4	Tungsten	Mortar	GGBFS	0.52		10% as cement replacement	35	-14.6	[31]
5	Coal	Mortar		0.30	Thermal activation	6 % as cement replacement	59	-1.7	[134]
6	Coal	Mortar		0.50	Clinkering	7% as clinker raw material	60	1.7	[132]
7	Coal	Mortar	-	0.50	Mechano-Thermal activation	20 % as cement replacement	55.7	-11.9	[76]
Alkali activated cements									
Sl. No	Type of tailing	Mix	Admixture		Activation Process	Percentage replacement	Maximum Compressive strength achieved (MPa)		Study

1	Vanadium	Mortar	Sodium hydroxide and Metakaolin	Thermo chemical activation (Alkaline roasting)	70 % mine tailing and 30% metakaolin	55.7	[135]
2	Kaolin	Paste	Sodium hydroxide, Sodium silicate,	Thermo mechanical treatment followed by Alkali activation	100% mine tailing	75	[29]
3	Boron	Mortar	Sodium silicate, sodium hydroxide	Thermo mechanical treatment followed by alkali activation	100 %	30.7	[55]
4	Tungsten	Mortar	calcium hydroxide, sodium hydroxide, sodium silicate	Thermal treatment followed by alkali activation	100%	75	[115]
5	Tungsten	Mortar	Sodium silicate, sodium hydroxide Potassium Hydroxide and ground granulated blast furnace slag	Alkali activation	90% mine waste and 10% GGBFS	33	[123]
Alkali activated material as a replacement of OPC							
1	Tungsten	Mortar	Sodium silicate, gypsum, lime	Mechano-chemical activation	30% cement replacement	56.95	[51]

665

27

4.3.1 Alkali Activated Binders

The mineral Albite, calcined in presence of alkali, when used as a one part cement achieved a strength of up to 44 MPa at 28 days [93]. Tungsten mine waste calcined in presence of Na_2CO_3, yields high early age strength up to 45 MPa on alkali activation with NaOH, and the strength decreases at later ages due to the formation of unstable compounds due to ineffective activator combination [104]. The molarity of NaOH solution found to have an effect on the development of compressive strength of binders with activated tungsten mine waste [104]. More specifically, about 18 MPa, 30 MPa and 70 MPa were achieved using 8 M, 14 M, and 24 M NaOH solution for activation of the waste, in presence of $Ca(OH)_2$. Geopolymers synthesized from non-calcined raw materials display a higher increase in the compressive strength in the later stage of the geopolymerisation reaction [129]. Jiao et al [135] indicated the curing temperature played an important role in strength gain of geopolymers with mine tailings where the compressive strength increased from 35.1 MPa to 55.7 MPa when the curing temperature was increased from 20 ^{o}C to 60 ^{o}C. At room temperature curing, the strength gain happens at a later age about at 14 days [85]. The feasibility of development of sodium silicate from mine tailing was studied. It was found that the sodium silicate produced from the tailings were able to successfully activate a metakaolin based system as geopolymers and achieve a strength up to 32.1 MPa as compared to a strength of 40 MPa by commercial sodium silicate [136].

4.3.2 Portland Cement Replacement and Supplementary Cementitious Material

Malagon et al [132] used 7% of coal mining waste as raw material for producing cement clinker and observed a 9-14% decrease in strength due to hindering of hydration by the Cu ions present in the mine waste. A replacement of 30% cement with phosphate tailings causes a decrease in flexural strength by 25% and compressive strength by 34.7%, 38.9%, 40.7% at 3 days, 28 days and 90 days, respectively [74]. Similar observation was made by Liu et al [128] where the compressive strength decreased from about 88 MPa to 35 MPa when the replacement percentage was 45%.

Martinez et al., [77] suggested when activated coal mine waste was used as cement replacement up to 20% attained strengths were at the 42.5 MPa class grade range whereas increasing the replacement to 50% performance dropped to 32.5 MPa class. Esmaeli and Aslani [44] proposed an optimum replacement percentage for copper mine tailings at which the compressive strength was greater than the control mixes by 5% and elastic modulus and split tensile strength were greater by 10% and 12 %, whereas Vargas and Lopez [91] reported all percentage of replacements lead to decrease in strength and use of copper mine tailing as an addition to the matrix as a filler improved the strength. Similarly, Liu et al found that at all water cement ratios the strength reduced with increase in graphite tailing content by up to 29% - 42% for 15% cement replacement due to free graphite and hydrocarbon oil leading to improper bonding and hydration [137]. Ince [39] reported a maximum compressive strength of about 37 MPa was achieved when the percentage replacement of cement by mine tailing was 30%, proving to be the optimum and all mine tailing mixes had compressive strength values higher than mixes with 100% cement. In their recent study, Ince et al [33] reported that the compressive strength of mixes increased with increasing percentage of mine tailings for both cement and lime mortars up to a replacement of 20% as shown in Fig 8. The mortars developed by Ince et al [33] were then used to join masonry units and it was found that the dewatering of the mortar (i.e. water movement towards the masonry) had an impact on the evolution of properties. When dewatering happened before curing the cement mortar mixes

with 20% mine tailing had approximately 20% lesser strength than that of control. The study also reported a reduction in split tensile and flexural strengths of the dewatered cement mortar with use of mine tailings whereas the same improved with increase in percentage of mine tailings for dewatered lime mortar. The mechanisms that underpin better behaviour in lime mortars are not yet well studied. Jian et al [138] observed that addition of up to 2-6% of mine tailing as a clinker raw material affected negatively the strength development of the cementitious matrix, with an exception of 2% replacement at 60 days. More specifically, for 0%, 2%, 4% and 6% replacement the strength of the cementitious matrix at 28 days was 44.1 MPa, 18.6 MPa, 11.3 MPa and 5.7 MPa respectively; while at 60 days it was 66.8 MPa,71.5 MPa, 48.9 MPa and 25.3 MPa respectively.

4.3.3 Filler
Existing data suggests that the use of mine tailings as fillers in cementitious matrices is also not conclusive. Some suggest that the filler effect can lead in the improvement of mechanical properties probably due to better packing, while others report reduction in properties. Sidique and Jang showed that incorporation of 5%, 10%, 15% and 20% mine tailings led to an increase of 3%,1%,10% and 16% in compressive strength and 2%, 5%, 24% and 17% in flexural strength respectively [133]. All the tailing added mixes had better resistance to abrasion and impact as compared to control concrete. However, Zheng et al [74] reported a decrease in performance of mortar mixes with increase in percentage of mine tailings. The study reported a 25% decrease in flexural strength and a 35.9% decrease in compressive strength for a 30% addition of mine tailing as a filler. This decrease in performance compared to control mixes could be due to the dilution effect as the study aimed reduction in cement usage by replacing cement by a filler.

It can be outlined from the past studies that obtaining a binder of high compressive strength up to 75 MPa is possible with the use of different mine tailings. However, the published results are not yet conclusive while at the same time there is a large spread of processing techniques and replacement percentages (for the tailings used). Therefore, there is a need for a systematic approach and clear understanding of: the mineralogy (and its variability) of tailings; suitable activation techniques; optimum duration of processing; choice of activator(s); optimum concentration of activator(s) and the percentage of replacement of cement in traditional cementitious binders.

4.4 Durability
The durability of the mine tailing binders was in most cases found to be a function of porosity and microstructure. The performance of mine tailings with respect to corrosion behaviour, chloride penetration and resistivity were affected by the presence of conductive elements such as graphite and iron. Though, the past studies do not indicate a standard trend in improvement or reduction in durability performance with increase in percentage of mine tailing, it was always observed in certain cases that optimum ranges for mine tailings' utilisation exist and within these optimum ranges the binders performed well.

4.4.1 Alkali Activated Binders
Jiao et al [82] reported a high thermal stability of geopolymer mixes with mine tailings. The compressive strength of the samples was unaffected up to an exposure temperature of 600°C, and it increased up to a temperature of 900°C due to densification. Ahmari and Zhang [139] found that there were no visible efflorescence, disintegration or cracks even after four months

of immersion in solutions of pH 4 and 7, however the unconfined compressive strength decreased by 59.3% and 53.3% from 11 MPa respectively, after immersion. A similar result was reported by Kiventera et al [130]. Their study showed that mine tailings mixed with pure NaOH produced a binder which performed poorly after immersion in water. However, the same performance was improved by use of ground granulated blast furnace slag in combination with tailings as a precursor. Falah et al [140] reduced the water absorption of alkali activated concrete with mine tailing by using 30% submicron sized mine tailings. Perumal et al [112] in their study reported that alkali activated mine tailing pastes exhibited a water absorption of 35%, 30%, 26%, 22.5% and 20% when the grinding time was varied from 1,2,4,8, 16 minutes respectively.

4.4.2 Portland Cement Replacement and Supplementary Cementitious Material

In general, water absorption of the mixes with mine waste were found to be higher than that of mixes with OPC and increased with increase in percentage of mine tailings [36,76]. When OPC was replaced by 50% coal mine waste, the water absorption increased by 32% [76]. However, Esmaeli and Aslani [44] reported that the water absorption decreased up to an optimum percentage of replacement and increased beyond that. In another study [44] mixes with optimum replacement ratio of 15% and 20% mine tailings had marginally lower water absorption (~2%), when compared to control concrete (2.4%). The depth of water absorption was also reported to decrease up to 20% replacement and increase beyond 20% cement replacement. Though the depth of water penetration increased after 20% replacement, it was still found to be less than control concrete (29.3 mm) at 30% replacement (24.2 mm) [44]. Similarly, Cheng [86] reported an optimum replacement percentage of 30% beyond which the performance of samples after immersion in water starts declining. Similar increase in trend was also observed in case of water absorption under pressure where the depth of water penetration for 0%, 20% and 50 % cement replacement was 3.6 mm, 6.5 mm and 15.8 mm respectively [76]. The study also reported primary absorption coefficient through capillary sorption measurements where it was similar for samples with 50% replacement and control mixes whereas samples with 20% replacement performed better than control. Ince et al [33] reported that water penetration depth and porosity increased with increase in percentage of mine tailings for cement mortar and decreased with increase in percentage of mine tailings for lime mortar. It is evident, that the reported data is scattered and to a certain extent confusing. Two studies that focused on freeze thaw performance concluded that the reduction in pore-size (as a result of the addition of mine tailings) led to a poor freeze thaw performance with the mixes containing graphite mine tailings reported a mass loss of about 5% after 25 cycles of freeze and thaw [39,45].

Ince reported that carbonation depth decreased from 9.8 mm to 5.6 mm for 30% cement replacement [39] whereas Cheng et al [86] reported that the carbonation depth increase with increase in percentage of mine tailings. However, the mixes with mine tailings had better compactness and were reported to be less porous. On the chloride ion penetration front, mixes with mine waste exhibited a better chloride resistance, irrespective of the type of mine waste used. The samples with 50% coal mine waste had a chloride resistance 5 times greater than that of control samples and samples exposed to chloride indicated the formation of Fridel's salt which was in line with the behaviour of samples with fly ash [77]. The chloride migration test indicated that the samples with mine tailings performed better than the control sample in chloride migration test. The samples with mine tailing fell in the category of high chloride diffusivity and the control samples were in the category of very high chloride diffusivity

810 [44]. A study on the corrosion development, found that the corrosion onset time increased
811 linearly with increase in percentage of mine waste, indicating that the mine tailings delayed
812 the initiation of corrosion [141]. Graphite tailing improved the electrical conductivity of concrete
813 which, on the other hand, can be problematic when it comes to corrosion. The surface
814 resistivity decreased from 62 kΩ·cm for normal concrete to 32 kΩ·cm for concrete with 15%
815 graphite tailing [49]. The surface change for samples with graphite tailing was almost twice as
816 that of control. The surface temperature reduced rapidly with increase in percentage of
817 graphite tailing [45].
818
819 ### 4.4.3 Filler
820 Incorporation mine tailings as fillers increased density and lowered water absorption and total
821 void content. After 24 hour of exposure to water the mixes with 20% mine tailings recorded a
822 11% decrease in rate of water absorption [133]. The mixes with 10% mine tailings were highly
823 resistant to sulphate attack. Though the mixes with 15% and 20% mine tailing exhibited higher
824 strength loss and weight loss compared to mixes with 10% mine tailings, all the mixes with
825 mine tailings performed better than control mixes. Similarly mixes with 10% mine tailing were
826 more resistant to acid attack [133]. Mass loss and depth of chloride penetration decreased
827 with increase in percentage of mine tailing, depth of penetration was 10.7 mm for control mixes
828 whilst 3.5-3.7 mm for mixes with mine tailing, similarly 4.3% and 3.4-3.7% mass loss for both
829 the mixes. The mass loss of the sample when exposed to HCL was 4.3% for control and 3.4%
830 - 3.7 % for samples with mine tailing [36]. Addition of mine tailing also increased the drying
831 shrinkage, however the drying shrinkage of mixes with 10% mine tailing was lower than the
832 mixes with 5%, 15%, 20% and 25% mine tailings [74].
833
834 Figure 15 shows published data on the variation of measured porosity for different
835 percentages of mine-tailings used in the binders.
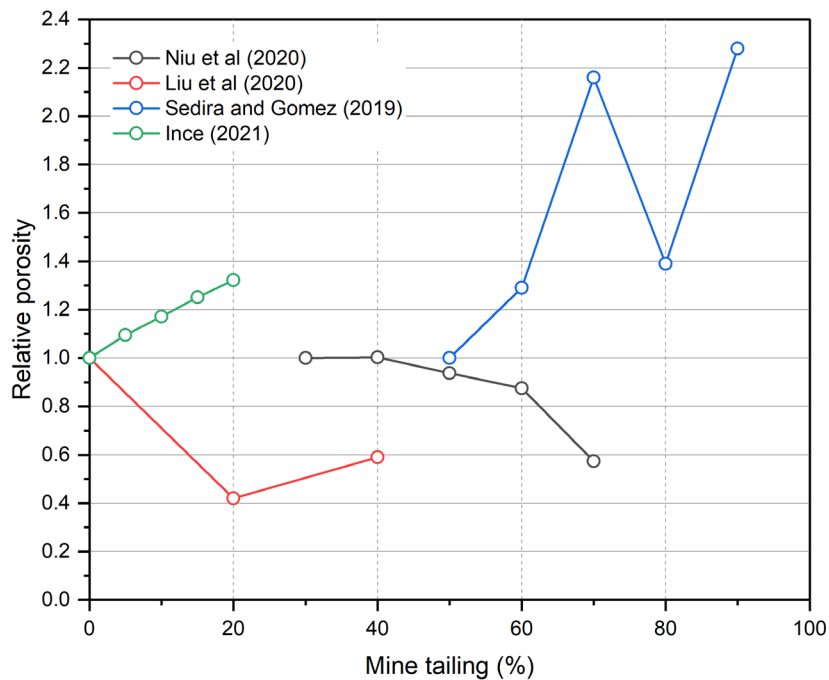
Fig. 15: Variation in porosity of samples with different percentages of mine tailings.

839 ### 4.5 Environmental Properties - Leaching of Heavy metals

Table 1 indicates that mine tailings are in general obtained with the presence of heavy metals such as Pb, Zn, Cd, Cu, Ar, Cr, V, Zr. This always poses a danger of leaching of heavy metals into the environment over the period when mine tailing is used as a construction material. Immobilising heavy metals is very critical in this discussion. Heavy metals can become a part of a 3-dimensional chain and thus get immobilised, and this process is known as locking. The ionic size and valence of the heavy metals are the major factors influencing locking.

4.5.1 Alkali Activated Binders

Wan et al., [70] studied immobilisation of lead from lead nitrate addition by alkali activation of sphalerite floatation mine tailing (Zinc tailings) using sodium silicate and reported that about 97.9 – 99.5% of heavy metals were immobilised when metakaolin was used as an additive and 92.26% were immobilised when only mine tailings were used. Similarly, for the same amount of alkali activated of tungsten mine waste the heavy metals leaching decreased with increase in percentage of GGBFS. In either case, the leaching value was less than the permissible value given by Korean guidelines, TCLP toxic limits [142] and European guidelines [143] for cadmium, zinc, copper and lead [31]. Gomes et al., [144] reported that alkali activated tungsten mine wastes when water cured stabilizes at a pH of 7 after about a week. This makes it fall within the range of 2-8.5 in which arsenic leaching is negligible. Peng et al., [51] reported that the Pb in tungsten mine waste are solidified in the garnet crystal and therefore cannot leach.

4.5.2 Portland Cement Replacement and Supplementary Cementitious Material

Ince [39] found that when sulphidic gold mine tailing was used as a cement or sand replacement the leaching was always within the limits specified by US Code of Federal Regulations (CFR). And it was also observed that when the percentage of replacement was higher the leaching was lower due to pore structure refinement. The Cr, Pb and Cd leached was 0.153, 0.0004, 0.00007 mg/ L when the percentage replacement was 10% and it decreased to 0.129, 0.0003 and 0.00005 mg/L respectively, when the percentage replacement was 30%. When compared with other standards it can also be seen that these wastes qualified as non-hazardous as per the TCLP toxic limits [142] and as non-toxic as per the framework for eco-toxic materials as per European guidelines [143]. Gou et al., [23] also reported that the clinkering and hydration of cement with mine tailing prevents the leaching of heavy metals when mine tailings are used as a cement replacement. In a similar line, Nouairi et al., [145] reported that 75% of Pb, 85% of Zn and 80% of Cu were immobilized by hydration of Zn-Pb mine tailings in mortar. Pyo et al., [68] reported that though the As, Pb, Zn and Cd content of quartz tailing were higher than the other silica powder their values were within the permissible limits. The study also reported the reduction in leaching due to physical and chemical encapsulation of heavy metals when used in ultrahigh performance concrete as supplementary cementitious material.

5. Future Outlook

Raw materials form the basis of our technological development in all sectors of our economies. From building and construction operations to the manufacture of bespoke electronic components, raw materials and minerals are important. World mining data shows significant increase in the extraction of mining products the last 35 years (Fig. 16).

(a)

(b)
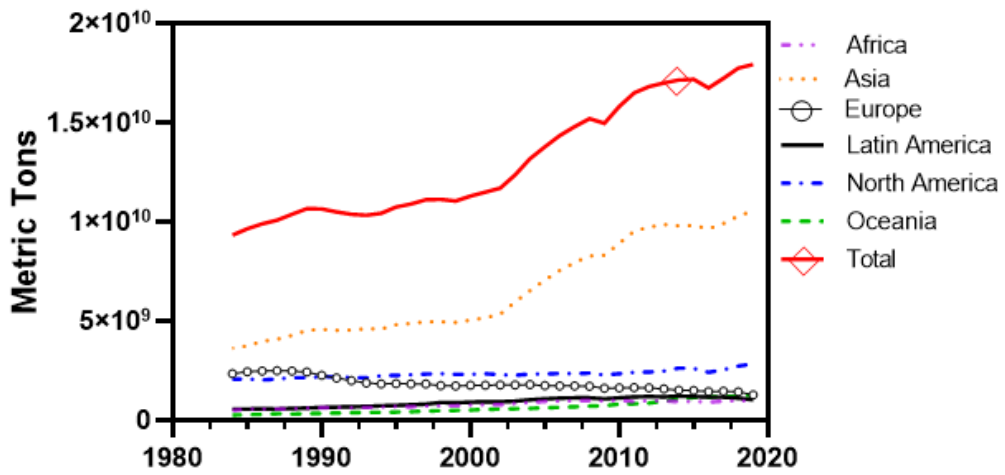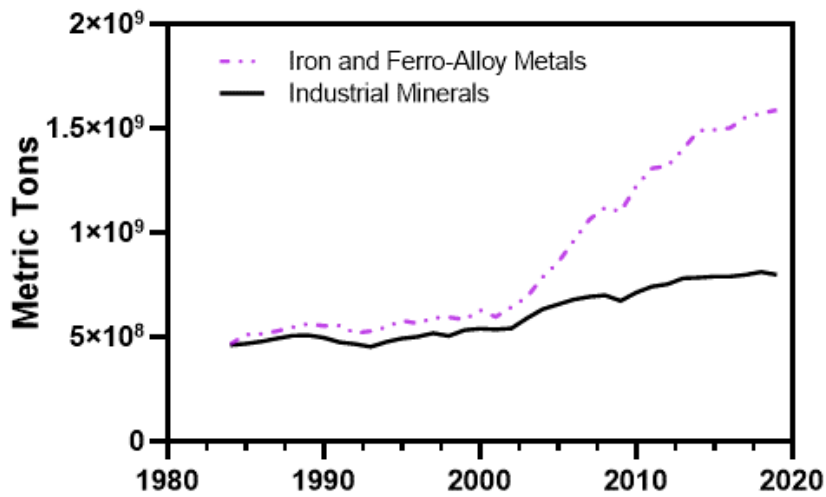
Fig. 16: Production of mining products between 1985 and 2020: (a) all mining products per geographical region and (b) global production of two major mining commodities (Data obtained from World Mining Data [146]).

Since 2000, there is a steady increase of mining production except for Europe. For Asia and Australia, this increase has been considerable (Fig. 17).

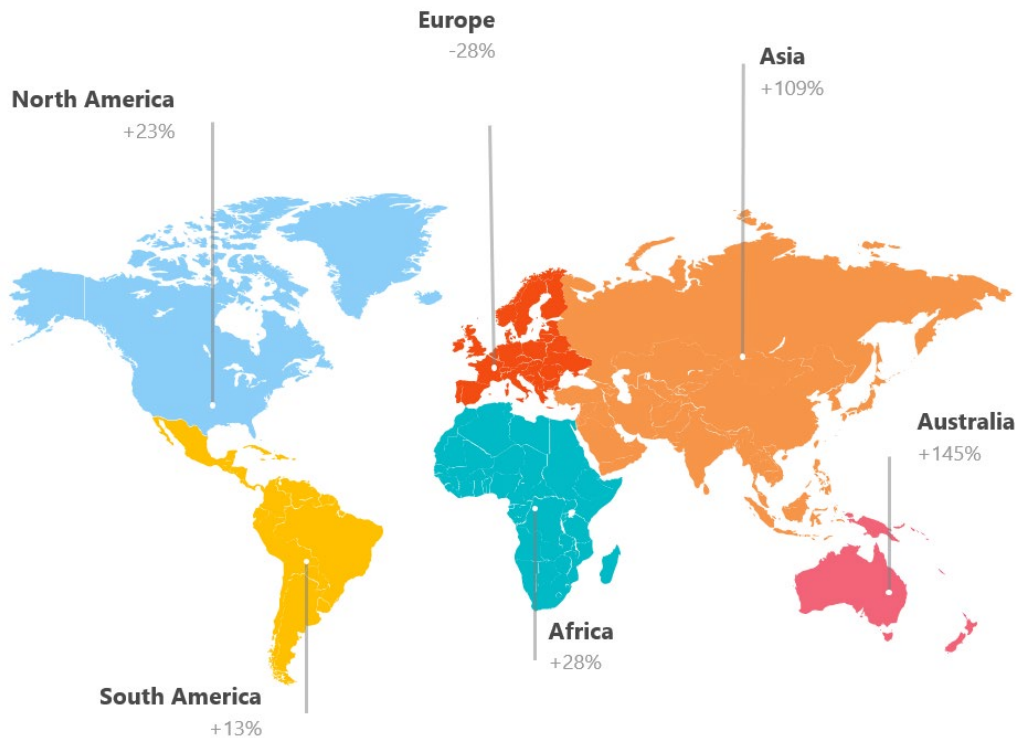**Fig. 17**: Production growth of mining products per geographic region between 2000 and 2020 (Data obtained from World Mining Data [146]).

At the same time, the sustainability goals (SDGs), which in many countries are now part of the legislation, have created the perfect growth conditions for low-carbon technologies. From wind turbines to solar panels and electric cars, these developments require vast volumes of minerals for production and manufacturing. Therefore, the road to a low-carbon sustainable future will be a very mineral intensive road. Industrial level mining directly and positively impacts: the development of good jobs and economic growth (SDG8); provides raw materials that support the development of renewable energy technologies (SDG7) which in turn facilitates innovation and infrastructure (SDG9). At the same time, it can negatively impact terrestrial ecosystems (SDG15) as well as sustainable clean water consumption and availability (SDG6). The effects of mining are also found to impact attaining the goals related to life below water (SDG14), actions related to climate change (SDG13), ensuring healthy lives for all communities (SDG 3) and responsible consumption and production patterns (SDG12) (www.undp.org). Taking these into consideration, the Responsible Mining Foundation proposed a framework for responsible mining [147]. This report declares tailings management as a major environmental responsibility and efficient tailing management shall improve good health (SDG3), sustainable cities and communities (SDG11), responsible consumption (SDG12), climate action (SDG13), life below water (SDG14). When the quantity of tailings disposed in land and into water bodies and confined dams are reduced contamination of land and water is avoided and hence improves life on land (SDG15) and clean water and sanitation (SDG6).

On the other side of this discussion is the construction sector, which is equally, if not more, responsible for heavy environmental burden. The civil infrastructure sector is global, is huge and utilises extraordinary volumes of materials for the manufacture of core construction composites. This contribution has highlighted the chemical and mineralogical similarities

between tailings and pristine raw materials used in the manufacture on cement-based binders. However, the current state-of-the-art in the field of utilising tailings in such binders albeit showing some promising results is limited and largely inconclusive as discussed in the preceding sections. A list of limitations for such use is given in Table 4. All these challenges highlight the importance of extensive and systematic research on this area, something that can lead to large scale valorisation of mineral waste streams in large manufacturing processes such as cement and concrete.

Table 4: Challenges for use of mine tailings in cementitious binders and potential solutions

Challenges	Potential solutions
Variability in property and quality of various mine streams	It is difficult to assign a single method of reuse/recycle for all wastes. However, proposing a classification system based on certain key parameters from characterisation and providing customised solution for each category shall be more practical from industry point of view. Clustering tailing streams and mapping their properties can allow the development upper/lower limits in their use, increasing the confidence of post-processors and/or end-users.
High crystallinity and non-reactive nature of mine tailings.	The reactivity of the mine tailings shall be improved by mechanical, thermal, or chemical activation. The field of mechanochemistry can provide vital assistance on this issue.
Presence of heavy metals and metalloids such as Hg, Pb, Cr, V, Cd, Mn, Zn etc in variable quantities is observed in mine tailings. This may leach into the environment when used in binders in construction.	Heavy metals and metalloids get encapsulated and are prevented from leaching when used in cementitious binder [23,145]. Also, under the umbrella of circular zero waste economy, options are being explored to mine heavy metals from the mine tailings before their disposal. This may help in removal of heavy metals prior to their disposal and eliminate the risk of leaching.[148].
Presence of Cu^{2+}, PO_3^{2+} which interfere with the hydration and setting processes.	The presence of such ions shall be noted, and the percentage of replacement shall be decided as to keep these ions within permissible limits. Cement technology methods can be utilised to alleviate hydration and/or setting issues.
Lack of guidelines and standards. The existing guidelines and standards do not explicitly provide a methodology for	More research and development should be carried out in this area to strengthen the knowledge data base to provide a rational approach and guideline towards use of mine

suitability assessment of mine tailing as an SCM or precursor for alkali activation.	tailings or any new waste in cementitious binder. Currently with advent of Horizon Europe program and the United Nations SDGs, various research and innovation projects are spearheaded in this direction.

936

937 Use of mine tailing in cementitious binders not only contributes to environmental, innovation
938 and health related benefits as discussed. It can also contribute to SDGs related to economy
939 and our sustainable urban/rural habitats such as the development of good jobs and economic
940 growth (SDG8) and making human settlements safer, more resilient and sustainable (SDG11).

941

942 The argument that the variability in mine waste streams is a limiting factor should not be a
943 "preventing" factor to commit to the use of mine tailing in cementitious binders. First of all, the
944 field has not been explored sufficiently and therefore there is no hard evidence that variability
945 is an issue or that it cannot be tackled. There is variability in fly-ash and ground granulated
946 blast furnace slag as well. This did not prevent their extensive utilisation in concrete technology
947 for almost 3.5 decades. Secondly, the fact that the research in this area is limited can be used
948 as a motivation for research and innovation to strengthen the means of implementation and
949 revitalize the global partnership for sustainable development (SDG17). It should contribute to
950 capacity development, science and technology towards these goals. Cement-based materials
951 research has dealt with such issues before. Not every fly-ash, slag or silica fume is the same
952 for example. Nonetheless, intensive research and development created the necessary
953 confidence on these, once novel and high-risk, supplementary cementitious materials, and
954 they have been used extensively for more than three decades now.

955

956 It is now time to draw our attention on different sources of cementitious materials and binders.
957 As discussed at the start of this article, it is now a common belief, even at institutional level
958 (e.g., European Cement Association), that new cementitious materials must be developed.
959 Mine tailings provide a great opportunity of sourcing raw materials for new binders without
960 further exploitation of natural resources. Detailed and systematic studies will contribute
961 towards this goal improving the level of confidence between engineers and manufacturers.
962 The impact of successful reuse of mine tailings will be enormous contributing significantly
963 towards the global sustainability goals.

964

965 **6. Conclusions**
966 The review of the past studies indicate that the mine tailings can be used as a direct cement
967 replacement or supplementary cementitious material or alkali activated cements based on the
968 chemical, mineralogical and physical properties. Their usage in most cases is after activation
969 of minerals in the mine tailing.

970

971 The process of activation involves creation of structural defects by grinding, heating or by alkali
972 activation. The choice of activation method is based on the minerals present in the mine
973 tailings. Calcination has been found to be highly effective in converting the crystalline phases
974 phyllo-silicate, hydroxide and carbonate minerals to amorphous phases. The grinding process
975 improves the reaction by increase in surface area, by reduction of particle size and by
976 developing new fractured surfaces and suitable of minerals of low hardness such as mica,
977 talc, clay minerals and other phyllo-silicates. When two different minerals of different hardness
978 are present the possibility of differential grinding has also been reported. Both grinding and

calcination are highly energy intensive and are counterproductive beyond the optimum duration. This emphasizes the significance the mineral phases have on the selection of activation methods. Alkali activation is also a potential route for processing mine tailings. With the change in alkali concentration and choice of alkali activators a strength range varying from 15 MPa – 75 MPa or even higher has been achieved. However, this process demands further understanding on formation of polymeric chains of C-A-S-H, N-A-S-H, K-A-S-H, C-(N)-A-S-H, N-F-(A)-S-H in presence different amounts of Ca, Si, Fe and Al ions and their stability. When a combination of two or more alkali activators are used the compatibility of one activator with another, and the minerals present in the precursor, play a critical role in terms of long-term strength. Activation processes can be complementary (e.g., mechano-chemical) but they always have to lead to the maximum benefits at minimum possible consumed energy.

The past studies indicate a high potential for use of mine tailings in cementitious binders. However, published literature also points out the lack of an activation method or mix design procedure which is more systematic rather than trial and error. Undoubtably, mine tailings provide a great source of raw materials for new binders without further exploitation of natural resources. Intensive and systematic research in this area will improve the level of confidence of engineers and manufacturers and can have a significant impact towards attaining the global sustainability goals.

Appendix – Published data on reactivity and activation processes

1028

1029 **Table A1:** Reactivity and activation processes of minerals present in mine tailings according to the existing literature

1030

Mineral/ Mineral group reported	Reactivity/ Property in raw form	Activation possibility	Literature
Albite	A crystalline alumina silicate mineral with formula $NaAlSi_3O_8$. Slow reactive and stable up to 1000 °C under normal conditions	Albite was completely amorphized when calcined at 1000 °C or 1150°C in presence of 50% NaOH or Na_2CO_3 respectively. Albite was observed to be stable at temperatures below 1000°C	(Feng et al., 2012; Perumal & Illikainen, 2019)
Amphibole	Inosilicate minerals of double chain SiO_4 tetrahedra with a better dissolubility as compared to Quartz	The amphibole phases decreased significantly when mixed with blast furnace slag, cement clinker and finely ground to a powder and mixed with warm water and cured at a temperature of 48±1 °C. Also, shall be used as a precursor for geopolymer.	(Huang et al., 2012; Kinnunen et al., 2018; Luukkonen et al., 2018)
Anatase	Anatase is a mineral form of TiO_2 and is crystalline. Anatase is less stable as compared to Rutile.	TiO_2 shall be immobilised in presence of phyllosilicates such as kaolinites. Admixtures prepared with anatase, alkali and phyllosilicates by calcination at 800 °C were found to improve compressive strength.by about 37%	(Zhang et al., 2017)

Ankerite	Ankerite is Ca(Fe, Mg, Mn)(CO$_3$)$_2$, and has properties similar to dolomite	Being a carbonate mineral ankerite is prone to decomposition at a temperature range of 650 ^{o}C to 850 ^{o}C	(Argane, Benzaazoua, et al., 2016)
Anorthite	Anorthite ((Ca,Na)(Si,Al)$_4$O$_8$) is a member of plagioclase feldspar member series	Quartz, calcite, and chlorite decompose to form anorthite at a firing temperature of about 1100 ^{o}C and contribute to the strength bricks and ceramics. However, Anorthite partially melts to liquid phase at 1200 ^{o}C. In presence of NaOH/ KOH dissolution of Si and Al in Anorthite happens to form reactive components	(Choi et al., 2009; Li et al., 2017; H. Xu & Van Deventer, 2002; Yang et al., 2014)
Apatite	Apatite is a group of phosphate mineral including hydroxyapatite (Ca$_5$(PO$_4$)$_3$(OH)), fluorapatite (Ca$_5$(PO$_4$)$_3$F$_2$) and chlorapatite (Ca$_5$(PO$_4$)$_3$Cl$_2$)	Apatite indicated no/ lesser solubility in presence of alkali. However, shall be used in heavy metal encapsulation in ceramics. In a basic environment at a temperature of about 550 ^{o}C the phosphates from apatite and Al react leading to decrease in apatite peaks.	(Kinnunen et al., 2018; Zheng et al., 2015)
Arsenopyrite	Arsenopyrite (FeAsS) is a hard Iron Arsenic Sulphide crystal. þ	When arsenopyrite was heated to 550 ^{o}C using microwaves Pyrite was formed. Arsenopyrite reacts with alkali and leaches As.	(Kiventerä et al., 2016; Pyo et al., 2018)

Augite	Augite is a chain silicate mineral with a stoichiometric formula $(Ca, Mg, Fe)_2(Si, Al)_2O_6$	Augite reacted when mixed with blast furnace slag, cement clinker and finely ground to a powder and mixed with warm water and cured at a temperature of $48\pm1\,^oC$.	(Huang et al., 2012; Hua Xu & Van Deventer, 2000)
Barite	Barite is a Barium sulphate mineral of formula $BaSO_4$	When used in mortar without treatment remained unaltered even till 180 days	(Argane et al., 2015)
Biotite	Biotite is a phyllosilicate mineral within the mica group of formula $K(Mg,Fe)_3AlSi_3O_{10}(F,OH)_2$ for the [i]th member	Biotite underwent partial decomposition in presence of sodium silicate	(Moukannaa et al., 2019)
Caldecahydrite	$CaAl_2O_4\,10H_2O$	It can be used in combination with other silicate minerals or other source of silica shall be considered for the use in binders	(Paiva et al., 2019)
Calcite	Calcite is calcium carbonate mineral of formula $CaCO_3$	The decomposition occurs completely at about 800 ^oC under calcination and at about 550 ^oC under alkali fusion.	(Frías et al., 2016; Moukannaa et al., 2019)
Chlorite	Chlorite is a group of phyllosilicate minerals and shall contribute to pozzolanic properties in raw form	Reactivity shall be improved by calcination	(Simonsen et al., 2020)
Clinochlore	Clinochlore is a member of chlorite group of minerals with the formula $(Mg,Fe)_6(Si,Al)_4O_{10}(OH)_8$	Structural decomposition of Clinochlore occurs at about 505 ^oC of calcination.	(Sedira et al., 2018; Yang et al., 2014)
Colemanite	Colemanite is a borate mineral of formula $Ca_2B_6O_{11}.5H_2O$	Colemanite decomposed forming CaO upon calcination up to 600 ^oC	(Aydln & Klzlltepe, 2019)
Corundum	Corundum is an Al_2O_3 mineral phase with better stability and crystallinity	Corundum disappeared on sintering above 1100 ^oC	(Liu et al., 2015)

		indicating decomposition and fusing to form other minerals depending on the elements present in the matrix	
Diaspore	Diaspore is an aluminium hydroxide mineral AlO(OH)	Diaspore turns to Corundum when calcined at a temperature of 800 $^\circ$C for 1 h The specific temperature of decomposition was at 510 $^\circ$C – 540 $^\circ$C.	(Ye et al., 2017). (Vangelatos et al., 2009)
Diopside	Diopside is a pyroxene mineral of formula, $CaMgSi_2O_6$	Alkaline roasting of diopside in presence of NaOH at 450 $^\circ$C led to its decomposition.	(Jiao et al., 2013)
Dolomite	Dolomite has a general formula of $MgCO_3 \cdot CaCO_3$.	Can play a role as an activator of pozzolans and shall also be used as a replacement of limestone. The peaks of dolomite, decreased significantly when mixed with blast furnace slag, cement clinker, and finely ground to a powder and mixed with warm water and cured at a temperature of 48±1 C. The decomposition of dolomite by dehydration and decarbonation processes complete at 850 °C of calcination.	(Huang et al., 2012; Moukannaa et al., 2019; Simonsen et al., 2020)
Feldspar	Feldspars are group of silicate minerals with calcium, aluminium, and potassium in it.	Completely dissolves in presence of a 10 M NaOH and shall be used as a	(Luukkonen et al., 2018; Yao et al., 2021; Young & Yang, 2019)

		precursor for alkali activated materials. Also decomposes while clinkering at a temperature of $1450\,^\circ$C Grinding up to 200 minutes increased the pozzolanic activity index of feldspar from 61% to 84%.	
Fluorite	Fluorite or fluorspar is a calcium fluorite mineral CaF_2	When used in mortar without treatment remained unaltered even till 180 days	(Argane et al., 2015)
Garnet	Garnet is a group of aluminium silicate minerals. It has high hardness, structural and chemical stability, and low cementitious property. It is also reported to have solidified chromium in it. It	Garnet minerals exhibited low dissolution in presence of alkali such as KOH and NaOH. However, garnet exhibited excellent geopolymerisation in presence of 20% metakaolin and 30% sodium silicate	(Peng et al., 2015; Wang et al., 2019; Hua Xu & Van Deventer, 2000)
Gypsum	Calcium sulphate mineral reacts with water and leads to expansion., $CaSO_4.\ 2H_2O$	Percentage shall be limited to 3.5 – 4% in the cement. Gypsum also reacts with alkalis and participates in geopolymerisation	(Kiventerä et al., 2016; Simonsen et al., 2020)
Hematite	Hematite is an Iron mineral of formula Fe_2O_3 and is abundant on the earth's crust.	Hematite in an alkaline medium produced by sodium metasilicate and in presence of other minerals reacted to form kinoferrosilite. Hematite also exhibited a thermal stability up to a temperature of $950\,^\circ$C.	(Buchwald et al., 2009; He et al., 2012; Krivenko et al., 2017)

		At temperatures greater than 1000 ℃ Hematite decomposed to produce magnetite and oxygen.	
Hydroboracite	Hydroboracite is a hydrated borate mineral of formula, $CaMg(B_3O_4((OH)_3)_2.3(H_2O)$	Hydroboracite decomposed at 600 ℃ of calcination	(Aydln & Klzlltepe, 2019)
Illite	Illite is a type of phyllosilicate clay mineral	At 10% of NaOH, Illite was dissolved at a temperature of 550 °C and Na-rich sodium aluminium silicate was formed. The dehydroxylation of illite generally occurs between 600 °C and 800 °C but the presence of alkali elements enhances the release of H_2O by hydrolysis and then the completion of the dehydroxylation process, however this hydroxylation has smaller effect on crystallinity.	(Fernandez et al., 2011; Moukannaa et al., 2019)
Kaolinite	$Al_2Si_2O_5(OH)_4$ or kaolinite is an alumina silicate crystalline mineral with Si/Al ratio equal to one. It in natural form shall act as an inert filler for supply of Al^{3+} ions	Turns to amorphous metakaolinite phases on calcination 750°C. This is one of the most important minerals used in geopolymerisation, A study considered geopolymerisation of sixteen different minerals mixed with kaolin. All sixteen mixes indicated higher strength in case of kaolinite addition,	(Komnitsas & Zaharaki, 2007; McIntosh et al., 2015; Perumal et al., 2019; Hua Xu & Van Deventer, 2000)

		due to increased dissolution of alumina in the matrix. However, kaolinite on calcination at 950°C recrystallizes and reduces the reactivity	
Magnetite	Magnetite is an iron mineral with chemical formula, Fe_3O_4	Magnetite exhibited lesser dissolution and reactivity in presence of alkali and phases were unaltered even after 28 days.	(Komnitsas & Zaharaki, 2007)
Mica	Mica is a group of phyllosilicate mineral.	It shall contribute to pozzolanic properties. The behaviour shall be improved by calcination till dehydroxylation	(Simonsen et al., 2020)
Montmorillonite	A soft phyllosilicate clay mineral system. On contact with water montmorillonite can swell many times its original volume	600-800 °C of calcination exhibited decrease in surface area and increased consumption of Ca(OH)2. However calcined montmorillonite does not have much influence on the microstructure. However, montmorillonite on grinding to a nano size becomes amorphous and improves microstructure and reduces permeability of concrete	(Chang et al., 2007; Fernandez et al., 2011)
Mullite	Mullite is an alumina silicate mineral of formula $Al_6Si_2O_{13}$	Mullite when formed in bricks and ceramics as a product of firing up to 1200 °C contributed to mechanical	(Chen et al., 2013; Cristelo et al., 2020)

		properties. However, in raw materials Mullite phases were found to be inert in presence of alkali.	
Muscovite	Phyllosilicate mineral of aluminium and potassium of formula $KAl_3SiO_{10}(OH)_2$	80 minutes of grinding reduces the crystallinity of muscovite by 37%. However, muscovite is identified to be mostly inert in case of alkali activation	(Cristelo et al., 2020; Yao et al., 2019)
Orthoclase	Orthoclase is a Feldspar mineral with formula $KAlSi_3O_8$	Orthoclase is capable of dissolution in alkali environment and hence geopolymerisation	(H. Xu & Van Deventer, 2002)
Palygorskite	Magnesium aluminium phyllosilicate clay mineral with water absorption capacity about 300% or more	Addition to cement leads to formation of interconnected fine pores.	(Lindgreen et al., 2008)
Pentlandite	Pentlandite is a sulphide mineral of formula $(Fe,Ni)_9S_8$	Pentlandite on oxidation leads to acid mine drainage	(Kossoff et al., 2014)
Phlogopite	Phlogopite is an end member of the biotite series of mica group $(KMg_3AlSi_3O_{10}(OH)_2$	The peaks phlogopite, decreased significantly when mixed with blast furnace slag, cement clinker and finely ground to a powder and mixed with warm water and cured at a temperature of 48 ± 1^oC. Melting, quenching and grinding of phlogopite improved alkali activity by 40%. Calcination of phlogopite up to 1200°C improved the	(Hartikainen & Helinä Hartikainen, 2008; Huang et al., 2012; Kinnunen et al., 2018; Sreenivasan et al., 2017)

		reactivity and at 1600°C was completely amorphous.	
Pyrite	Iron sulphide mineral (FeS_2) in presence of water and oxidation leads to acid mine drainage	On hydration in presence of OPC pyrites produce ettringite and in presence of alkalis pyrites undergo alkali oxidation	(Argane et al., 2015; Kiventerä et al., 2016)
Pyrrhotite	Iron sulphide mineral of formula $Fe_{1-x}S$,	Leads to acid mine drainage on oxidation and is more reactive than pyrite	(Kiventerä et al., 2016; Sephton et al., 2019)
Quartz	Inert silicate mineral, SiO_2	Mine tailings with high amount of quartz has been used as aggregates	(Kiventerä et al., 2020)
Rutile	TiO_2. More inert compared to anatase. Contributes to photocatalytic effect		(Zhang et al., 2017)
Sanidine	K- Feldspar $K(AlSi_3O_8)$	Sanidine acted as a source of AL in alkali environment, however complete dissolution did not take place.	(Ahmari & Zhang, 2012, 2013)
Siderite	Crystalline Iron carbonate mineral	Transformed to magnetite on calcination	(Castro-Gomes et al., 2012; Obenaus-Emler et al., 2020)
Smithsonite	$ZnCO_3$	Calcination leads to decarboxylation	(Argane, El Adnani, et al., 2016)
Talc	Talc is a phyllosilicate mineral	Milling more than 30 minutes led to reaggregation of particles.	(Hajimohammadi & van Deventer, 2016)

1031

1032

1033

1034

References

[1]   United Nations Data Booklet, The World's Cities in 2018, (n.d.).
      https://www.un.org/en/events/citiesday/assets/pdf/the_worlds_cities_in_2018_data_booklet.pdf
      (accessed September 15, 2021).

[2]   OECD, Global Material Resources Outlook to 2060, OECD Publishing, Paris, 2019.
      https://doi.org/https://doi.org/10.1787/9789264307452-en.

[3]   A. Torres, J. Brandt, K. Lear, J. Liu, A looming tragedy of the sand commons, Science. 357
      (2017) 970–971. https://doi.org/10.1126/science.aao0503.

[4]   J. Gale, J. Bradshaw, Z. Chen, A. Garg, D. Gomez, H.-H. Rogner, D. Simbeck, R. Williams, F.
      Toth, D. Van Vuuren, Sources of CO2, IPCC Spec. Rep. Carbon Dioxide Capture Storage.
      (2005) 77–103. https://doi.org/10.1021/es200619j.

[5]   S.-E. Ouldboukhitine, R. Belarbi, I. Jaffal, A. Trabelsi, Assessment of green roof thermal
      behavior: A coupled heat and mass transfer model, Build. Environ. 46 (2011) 2624–2631.
      https://doi.org/10.1016/j.buildenv.2011.06.021.

[6]   G. Heravi, T. Nafisi, R. Mousavi, Evaluation of energy consumption during production and
      construction of concrete and steel frames of residential buildings, Energy Build. 130 (2016)
      244–252. https://doi.org/10.1016/j.enbuild.2016.08.067.

[7]   G. Blight, Mine Waste: A Brief Overview of Origins, Quantities, and Methods of Storage,
      Waste. (2011) 77–88. https://doi.org/10.1016/B978-0-12-381475-3.10005-1.

[8]   J.S. Adiansyah, M. Rosano, S. Vink, G. Keir, A framework for a sustainable approach to mine
      tailings management: Disposal strategies, J. Clean. Prod. 108 (2015) 1050–1062.
      https://doi.org/10.1016/j.jclepro.2015.07.139.

[9]   D. Kossoff, W.E. Dubbin, M. Alfredsson, S.J. Edwards, M.G. Macklin, K.A. Hudson-Edwards,
      Mine tailings dams: Characteristics, failure, environmental impacts, and remediation, Appl.
      Geochemistry. 51 (2014) 229–245. https://doi.org/10.1016/j.apgeochem.2014.09.010.

[10] J. Lehne, F. Preston, Chatham House Report: Making Concrete Change - Innovation in Low-
      carbon Cement and Concrete, 2018.

[11] I.E. Agency, Technology Roadmap - Low-Carbon Transition in the Cement Industry: Foldout,
      2018. https://doi.org/10.1007/springerreference_7300.

[12] EU Commission, The European Green Deal, Eur. Comm. 53 (2019) 24. https://eur-
      lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52019DC0640&from=EN.

[13] K.L. Scrivener, V.M. John, E.M. Gartner, Eco-efficient cements: Potential economically viable
      solutions for a low-CO2 cement-based materials industry, Cem. Concr. Res. 114 (2018) 2–26.
      https://doi.org/10.1016/j.cemconres.2018.03.015.

[14] W. Shanks, C.F. Dunant, M.P. Drewniok, R.C. Lupton, A. Serrenho, J.M. Allwood, How much
      cement can we do without? Lessons from cement material flows in the UK, Resour. Conserv.
      Recycl. 141 (2019) 441–454. https://doi.org/10.1016/j.resconrec.2018.11.002.

[15] M.C.G. Juenger, R. Snellings, S.A. Bernal, Supplementary cementitious materials: New
      sources, characterization, and performance insights, Cem. Concr. Res. 122 (2019) 257–273.
      https://doi.org/10.1016/j.cemconres.2019.05.008.

[16] R. Obenaus-Emler, M. Falah, M. Illikainen, Assessment of mine tailings as precursors for
      alkali-activated materials for on-site applications, Constr. Build. Mater. 246 (2020) 118470.
      https://doi.org/https://doi.org/10.1016/j.conbuildmat.2020.118470.

[17] W. Li, W. Lin, Chapter 7 Circular Economy Policies in China, in: Towar. a Circ. Econ. Corp.
      Manag. Policy Pathways. ERIA Res. Proj. Rep. 2014-44, 2016: pp. 95–111.

[18] J.R. Owen, D. Kemp, Lèbre, K. Svobodova, G. Pérez Murillo, Catastrophic tailings dam
      failures and disaster risk disclosure, Int. J. Disaster Risk Reduct. 42 (2020).
      https://doi.org/10.1016/j.ijdrr.2019.101361.

[19] W. Cornwall, Catastrophic failures raise alarm about dams containing muddy mine wastes,
      Science (80-.). (2020). https://doi.org/10.1126/science.abe3917.

[20] L.H. Silva Rotta, E. Alcântara, E. Park, R.G. Negri, Y.N. Lin, N. Bernardo, T.S.G. Mendes,
      C.R. Souza Filho, The 2019 Brumadinho tailings dam collapse: Possible cause and impacts of
      the worst human and environmental disaster in Brazil, Int. J. Appl. Earth Obs. Geoinf. 90
      (2020) 102119. https://doi.org/10.1016/j.jag.2020.102119.

[21] B. Oberle, S. Bringezu, S. Hatfield-dodds, S. Hellweg, H. Schandl, J. Clement, C. Authors, L.
      Cabernard, N. Che, D. Chen, H. Droz-georget, P. Ekins, M. Fischer-kowalski, M. Flörke, S.
      Frank, A. Froemelt, A. Geschke, M. Haupt, P. Havlik, R. Hüfner, M. Lenzen, M. Lieber, B. Liu,
      Y. Lu, S. Lutter, J. Mehr, A. Miatto, D. Newth, C. Oberschelp, S. Pfister, E. Piccoli, R.
      Schaldach, J. Schüngel, T. Sonderegger, A. Sudheshwar, E. Van Der Voet, C. Walker, J.
      West, Z. Wang, B. Zhu, Global Resources Outlook 2019: Natural resources for the future we

1095		want, United Nations Environment Programme, 2019.
1096	[22]	S. Solismaa, M. Räisänen, A. Ismailov, M. Karhu, H. Sreenivasan, P. Kinnunen, M. Illikainen,
1097		M. Lehtonen, Valorization of finnish mining tailings for use in the ceramics industry, Bull. Geol.
1098		Soc. Finl. 90 (2018). https://doi.org/10.17741/bgsf/90.1.002.
1099	[23]	M. Gou, L. Zhou, N.W.Y. Then, Utilization of tailings in cement and concrete: A review, Sci.
1100		Eng. Compos. Mater. 26 (2019) 449–464. https://doi.org/10.1515/secm-2019-0029.
1101	[24]	WBCSD, Cement Industry Energy and CO2 Performance: Getting the Numbers Right, 2016.
1102	[25]	W.E. Forum, The Next Frontier: Natural Resource Targets Shaping a Competitive Circular
1103		Economy within Planetary Boundaries, Geneva, 2019.
1104	[26]	M. Benzaazoua, H. Bouzahzah, Y. Taha, L. Kormos, D. Kabombo, F. Lessard, B. Bussière, I.
1105		Demers, M. Kongolo, Integrated environmental management of pyrrhotite tailings at Raglan
1106		Mine: Part 1 challenges of desulphurization process and reactivity prediction, J. Clean. Prod.
1107		162 (2017) 86–95. https://doi.org/10.1016/j.jclepro.2017.05.161.
1108	[27]	Y. Wang, T. an Zhang, Y. Zhang, G. Lyu, W. Zhang, Mineral transformation in treating low-
1109		grade bauxite using the calcification–carbonization process and preparing cement clinker with
1110		the obtained residue, Miner. Eng. 138 (2019) 139–147.
1111		https://doi.org/10.1016/j.mineng.2019.04.031.
1112	[28]	B. Bussière, Colloquium 2004: Hydrogeotechnical properties of hard rock tailings from metal
1113		mines and emerging geoenvironmental disposal approaches, Can. Geotech. J. 44 (2007)
1114		1019–1052. https://doi.org/10.1139/T07-040.
1115	[29]	M.A. Longhi, E.D. Rodríguez, S.A. Bernal, J.L. Provis, A.P. Kirchheim, Valorisation of a kaolin
1116		mining waste for the production of geopolymers, J. Clean. Prod. 115 (2016) 265–272.
1117		https://doi.org/10.1016/j.jclepro.2015.12.011.
1118	[30]	A.M.T. Simonsen, S. Solismaa, H.K. Hansen, P.E. Jensen, Evaluation of mine tailings'
1119		potential as supplementary cementitious materials based on chemical, mineralogical and
1120		physical characteristics, Waste Manag. 102 (2020) 710–721.
1121		https://doi.org/10.1016/j.wasman.2019.11.037.
1122	[31]	Y.W. Choi, Y.J. Kim, O. Choi, K.M. Lee, M. Lachemi, Utilization of tailings from tungsten mine
1123		waste as a substitution material for cement, Constr. Build. Mater. 23 (2009) 2481–2486.
1124		https://doi.org/10.1016/j.conbuildmat.2009.02.006.
1125	[32]	I. Vangelatos, G.N. Angelopoulos, D. Boufounos, Utilization of ferroalumina as raw material in
1126		the production of Ordinary Portland Cement, J. Hazard. Mater. 168 (2009) 473–478.
1127		https://doi.org/10.1016/j.jhazmat.2009.02.049.
1128	[33]	C. Ince, S. Derogar, K. Gurkaya, R.J. Ball, Properties, durability and cost efficiency of cement
1129		and hydrated lime mortars reusing copper mine tailings of Lefke-Xeros in Cyprus, Constr.
1130		Build. Mater. 268 (2021) 121070. https://doi.org/10.1016/j.conbuildmat.2020.121070.
1131	[34]	A.P. Vilela, T.M.C. Eugênio, F.F. de Oliveira, J.F. Mendes, A.G.C. Ribeiro, L.E.V. de S.
1132		Brandão Vaz, R.F. Mendes, Technological properties of soil-cement bricks produced with iron
1133		ore mining waste, Constr. Build. Mater. 262 (2020) 120883.
1134		https://doi.org/10.1016/j.conbuildmat.2020.120883.
1135	[35]	L. Yu, Z. Zhang, X. Huang, B. Jiao, D. Li, Enhancement experiment on cementitious activity of
1136		copper-mine tailings in a geopolymer system, Fibers. 5 (2017) 1–15.
1137		https://doi.org/10.3390/fib5040047.
1138	[36]	O. Onuaguluchi, Ö. Eren, Recycling of copper tailings as an additive in cement mortars,
1139		Constr. Build. Mater. 37 (2012) 723–727. https://doi.org/10.1016/j.conbuildmat.2012.08.009.
1140	[37]	F. Pacheco-Torgal, J. Castro-Gomes, S. Jalali, Tungsten mine waste geopolymeric binder:
1141		Preliminary hydration products investigations, Constr. Build. Mater. 23 (2009) 200–209.
1142		https://doi.org/10.1016/j.conbuildmat.2008.01.003.
1143	[38]	N. Cristelo, J. Coelho, M. Oliveira, N.C. Consoli, Á. Palomo, A. Fernández-Jiménez, Recycling
1144		and application of mine tailings in alkali-activated cements and mortars-strength development
1145		and environmental assessment, Appl. Sci. 10 (2020). https://doi.org/10.3390/app10062084.
1146	[39]	C. Ince, Reusing gold-mine tailings in cement mortars: Mechanical properties and socio-
1147		economic developments for the Lefke-Xeros area of Cyprus, J. Clean. Prod. 238 (2019)
1148		117871. https://doi.org/10.1016/j.jclepro.2019.117871.
1149	[40]	P. Savva, M.F. Petrou, Highly absorptive normal weight aggregates for internal curing of
1150		concrete, Constr. Build. Mater. 179 (2018) 80–88.
1151		https://doi.org/10.1016/j.conbuildmat.2018.05.205.
1152	[41]	P. Savva, D. Nicolaides, M.F. Petrou, Internal curing for mitigating high temperature concreting
1153		effects, Constr. Build. Mater. 179 (2018) 598–604.
1154		https://doi.org/10.1016/j.conbuildmat.2018.04.032.

1155 [42] M. Alazhari, T. Sharma, A. Heath, R. Cooper, K. Paine, Application of expanded perlite
1156   encapsulated bacteria and growth media for self-healing concrete, Constr. Build. Mater. 160
1157   (2018) 610–619. https://doi.org/10.1016/j.conbuildmat.2017.11.086.
1158 [43] R. Alghamri, A. Kanellopoulos, C. Litina, Preparation and polymeric encapsulation of powder
1159   mineral pellets for self-healing cement based materials, Constr. Build. Mater. 186 (2018) 247–
1160   262. https://doi.org/10.1016/j.conbuildmat.2018.07.128.
1161 [44] J. Esmaeili, H. Aslani, Use of copper mine tailing in concrete: strength characteristics and
1162   durability performance, J. Mater. Cycles Waste Manag. 21 (2019) 729–741.
1163   https://doi.org/10.1007/s10163-019-00831-7.
1164 [45] Z.R. Wang, B. Li, H.B. Liu, Y.X. Zhang, X. Qin, Degradation characteristics of graphite tailings
1165   cement mortar subjected to freeze-thaw cycles, Constr. Build. Mater. 234 (2020) 117422.
1166   https://doi.org/10.1016/j.conbuildmat.2019.117422.
1167 [46] R. Argane, M. El Adnani, M. Benzaazoua, H. Bouzahzah, A. Khalil, R. Hakkou, Y. Taha,
1168   Geochemical behavior and environmental risks related to the use of abandoned base-metal
1169   tailings as construction material in the upper-Moulouya district, Morocco, Environ. Sci. Pollut.
1170   Res. 23 (2016) 598–611. https://doi.org/10.1007/s11356-015-5292-y.
1171 [47] J. Kiventerä, P. Perumal, J. Yliniemi, M. Illikainen, Mine tailings as a raw material in alkali
1172   activation: A review, Int. J. Miner. Metall. Mater. 27 (2020) 1009–1020.
1173   https://doi.org/10.1007/s12613-020-2129-6.
1174 [48] R. Argane, M. Benzaazoua, A. Bouamrane, R. Hakkou, Cement hydration and durability of low
1175   sulfide tailings-based renders: A case study in Moroccan constructions, Miner. Eng. 76 (2015)
1176   97–108. https://doi.org/10.1016/j.mineng.2014.10.022.
1177 [49] H. Liu, K. Liu, Z. Lan, D. Zhang, Mechanical and Electrical Characteristics of Graphite Tailing
1178   Concrete, Adv. Mater. Sci. Eng. 2018 (2018). https://doi.org/10.1155/2018/9297628.
1179 [50] G. Yao, Q. Liu, J. Wang, P. Wu, X. Lyu, Effect of mechanical grinding on pozzolanic activity
1180   and hydration properties of siliceous gold ore tailings, J. Clean. Prod. 217 (2019) 12–21.
1181   https://doi.org/10.1016/j.jclepro.2019.01.175.
1182 [51] K. Peng, H. Yang, J. Ouyang, Tungsten tailing powders activated for use as cementitious
1183   material, Powder Technol. 286 (2015) 678–683. https://doi.org/10.1016/j.powtec.2015.09.012.
1184 [52] A. Sicakova, M. Kovac, Technological characterisation of selected mineral additives, IOP Conf.
1185   Ser. Mater. Sci. Eng. Construmet. (2018) 1–6. https://doi.org/10.1088/1757-
1186   899X/385/1/012048.
1187 [53] C. Shi, P. V. Krivenko, D. Roy, Alkali-Activated Cements and Concretes, CRC Press. 03
1188   (2003).
1189 [54] P. Kinnunen, A. Ismailov, S. Solismaa, H. Sreenivasan, M.L. Räisänen, E. Levänen, M.
1190   Illikainen, Recycling mine tailings in chemically bonded ceramics – A review, J. Clean. Prod.
1191   174 (2018) 634–649. https://doi.org/10.1016/j.jclepro.2017.10.280.
1192 [55] S. Aydln, C.Ç. Klzlltepe, Valorization of Boron Mine Tailings in Alkali-Activated Mortars, J.
1193   Mater. Civ. Eng. 31 (2019) 1–12. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002871.
1194 [56] S. Ahmari, L. Zhang, Utilization of cement kiln dust (CKD) to enhance mine tailings-based
1195   geopolymer bricks, Constr. Build. Mater. 40 (2013) 1002–1011.
1196   https://doi.org/10.1016/j.conbuildmat.2012.11.069.
1197 [57] S. Moukannaa, A. Nazari, A. Bagheri, M. Loutou, J.G. Sanjayan, R. Hakkou, Alkaline fused
1198   phosphate mine tailings for geopolymer mortar synthesis: Thermal stability, mechanical and
1199   microstructural properties, J. Non. Cryst. Solids. 511 (2019) 76–85.
1200   https://doi.org/10.1016/j.jnoncrysol.2018.12.031.
1201 [58] Y. Chen, Y. Zhang, T. Chen, T. Liu, J. Huang, Preparation and characterization of red
1202   porcelain tiles with hematite tailings, Constr. Build. Mater. 38 (2013) 1083–1088.
1203   https://doi.org/10.1016/j.conbuildmat.2012.06.056.
1204 [59] S. Wang, Preparation of foam concrete from graphite tailing, Adv. Mater. Res. 356–360 (2012)
1205   1994–1997. https://doi.org/10.4028/www.scientific.net/AMR.356-360.1994.
1206 [60] G. Zhang, Y. Yan, Z. Hu, B. Xiao, Investigation on preparation of pyrite tailings-based mineral
1207   admixture with photocatalytic activity, Constr. Build. Mater. 138 (2017) 26–34.
1208   https://doi.org/10.1016/j.conbuildmat.2017.01.134.
1209 [61] H. Xu, J.S.J. Van Deventer, The geopolymerisation of alumino-silicate minerals, Int. J. Miner.
1210   Process. 59 (2000) 247–266. https://doi.org/10.1016/S0301-7516(99)00074-5.
1211 [62] H. Xu, J.S.J. Van Deventer, Factors affecting the geopolymerization of alkali-feldspars, Miner.
1212   Metall. Process. 19 (2002) 209–214. https://doi.org/10.1007/bf03403271.
1213 [63] J. Ye, W. Zhang, D. Shi, Properties of an aged geopolymer synthesized from calcined ore-
1214   dressing tailing of bauxite and slag, Cem. Concr. Res. 100 (2017) 23–31.

1215   https://doi.org/10.1016/j.cemconres.2017.05.017.

1216 [64] M. Frías, M.I. Sanchez De Rojas, R. García, A. Juan Valdés, C. Medina, Effect of activated
1217   coal mining wastes on the properties of blended cement, Cem. Concr. Compos. 34 (2012)
1218   678–683. https://doi.org/10.1016/j.cemconcomp.2012.02.006.

1219 [65] J. Zheng, Y. Zhu, Z. Zhao, Utilization of limestone powder and water-reducing admixture in
1220   cemented paste backfill of coarse copper mine tailings, Constr. Build. Mater. 124 (2016) 31–
1221   36. https://doi.org/10.1016/j.conbuildmat.2016.07.055.

1222 [66] Y. Chen, Y. Zhang, T. Chen, Y. Zhao, S. Bao, Preparation of eco-friendly construction bricks
1223   from hematite tailings, Constr. Build. Mater. 25 (2011) 2107–2111.
1224   https://doi.org/10.1016/j.conbuildmat.2010.11.025.

1225 [67] S. Moukannaa, M. Loutou, M. Benzaazoua, L. Vitola, J. Alami, R. Hakkou, Recycling of
1226   phosphate mine tailings for the production of geopolymers, J. Clean. Prod. 185 (2018) 891–
1227   903. https://doi.org/10.1016/j.jclepro.2018.03.094.

1228 [68] S. Pyo, M. Tafesse, B.J. Kim, H.K. Kim, Effects of quartz-based mine tailings on
1229   characteristics and leaching behavior of ultra-high performance concrete, Constr. Build. Mater.
1230   166 (2018) 110–117. https://doi.org/10.1016/j.conbuildmat.2018.01.087.

1231 [69] B. Wei, Y. Zhang, S. Bao, Preparation of geopolymers from vanadium tailings by mechanical
1232   activation, Constr. Build. Mater. 145 (2017) 236–242.
1233   https://doi.org/10.1016/j.conbuildmat.2017.03.234.

1234 [70] Q. Wan, F. Rao, S. Song, R. Morales-Estrella, X. Xie, X. Tong, Chemical forms of lead
1235   immobilization in alkali-activated binders based on mine tailings, Cem. Concr. Compos. 92
1236   (2018) 198–204. https://doi.org/10.1016/j.cemconcomp.2018.06.011.

1237 [71] H. Paiva, J. Yliniemi, M. Illikainen, F. Rocha, V.M. Ferreira, Mine tailings geopolymers as
1238   awaste management solution for a more sustainable habitat, Sustain. 11 (2019).
1239   https://doi.org/10.3390/su11040995.

1240 [72] R. Argane, M. Benzaazoua, R. Hakkou, A. Bouamrane, A comparative study on the practical
1241   use of low sulfide base-metal tailings as aggregates for rendering and masonry mortars, J.
1242   Clean. Prod. 112 (2016) 914–925. https://doi.org/10.1016/j.jclepro.2015.06.004.

1243 [73] R. Menezes, F. Farias, M.F. Oliveira, L.N.L. Santana, G.A. Neves, H.L. Lira, H.C. Ferreira,
1244   Kaolin processing waste applied in the manufacturing of ceramic tiles and mullite bodies,
1245   Waste Manag. Res. 27 (2009) 78–86. https://doi.org/10.1177/0734242X07085338.

1246 [74] K. Zheng, J. Zhou, M. Gbozee, Influences of phosphate tailings on hydration and properties of
1247   Portland cement, Constr. Build. Mater. 98 (2015) 593–601.
1248   https://doi.org/10.1016/j.conbuildmat.2015.08.115.

1249 [75] R. Hakkou, M. Benzaazoua, B. Bussière, Valorization of Phosphate Waste Rocks and Sludge
1250   from the Moroccan Phosphate Mines: Challenges and Perspectives, Procedia Eng. 138 (2016)
1251   110–118. https://doi.org/10.1016/j.proeng.2016.02.068.

1252 [76] L. Caneda-Martínez, C. Medina, M.I. Sánchez de Rojas, M. Frías, Water transport in binary
1253   eco-cements containing coal mining waste, Cem. Concr. Compos. 104 (2019) 103373.
1254   https://doi.org/10.1016/j.cemconcomp.2019.103373.

1255 [77] L. Caneda-Martínez, M. Frías, C. Medina, M.I.S. de Rojas, N. Rebolledo, J. Sánchez,
1256   Evaluation of chloride transport in blended cement mortars containing coal mining waste,
1257   Constr. Build. Mater. 190 (2018) 200–210. https://doi.org/10.1016/j.conbuildmat.2018.09.158.

1258 [78] S. Ahmari, L. Zhang, Production of eco-friendly bricks from copper mine tailings through
1259   geopolymerization, Constr. Build. Mater. 29 (2012) 323–331.
1260   https://doi.org/10.1016/j.conbuildmat.2011.10.048.

1261 [79] X.Y. Huang, W. Ni, W.H. Cui, Z.J. Wang, L.P. Zhu, Preparation of autoclaved aerated concrete
1262   using copper tailings and blast furnace slag, Constr. Build. Mater. 27 (2012) 1–5.
1263   https://doi.org/10.1016/j.conbuildmat.2011.08.034.

1264 [80] I. Sheikhhosseini Lori, M.M. Toufigh, V. Toufigh, Improvement of poorly graded sandy soil by
1265   using copper mine tailing dam sediments-based geopolymer and silica fume, Constr. Build.
1266   Mater. 281 (2021) 122591. https://doi.org/10.1016/j.conbuildmat.2021.122591.

1267 [81] I. Silva, J.P. Castro-Gomes, A. Albuquerque, Effect of immersion in water partially alkali-
1268   activated materials obtained of tungsten mine waste mud, Constr. Build. Mater. 35 (2012)
1269   117–124. https://doi.org/10.1016/j.conbuildmat.2012.02.069.

1270 [82] X. Jiao, Y. Zhang, T. Chen, Thermal stability of a silica-rich vanadium tailing based
1271   geopolymer, Constr. Build. Mater. 38 (2013) 43–47.
1272   https://doi.org/10.1016/j.conbuildmat.2012.06.076.

1273 [83] F. Lessard, B. Bussière, J. Côté, M. Benzaazoua, V. Boulanger-Martel, L. Marcoux, Integrated
1274   environmental management of pyrrhotite tailings at Raglan Mine: Part 2 desulphurized tailings

1275		as cover material, J. Clean. Prod. 186 (2018) 883–893.
1276		https://doi.org/10.1016/j.jclepro.2018.03.132.
1277	[84]	Z. Wei, J. Zhao, W. Wang, Y. Yang, S. Zhuang, Utilizing gold mine tailings to produce sintered
1278		bricks, Constr. Build. Mater. 282 (2021) 122655.
1279		https://doi.org/10.1016/j.conbuildmat.2021.122655.
1280	[85]	B. Koohestani, P. Mokhtari, E. Yilmaz, F. Mahdipour, A.K. Darban, Geopolymerization
1281		mechanism of binder-free mine tailings by sodium silicate, Constr. Build. Mater. 268 (2021)
1282		121217. https://doi.org/10.1016/j.conbuildmat.2020.121217.
1283	[86]	Y. Cheng, F. Huang, S. Qi, W. Li, R. Liu, G. Li, Durability of concrete incorporated with
1284		siliceous iron tailings, Constr. Build. Mater. 242 (2020) 118147.
1285		https://doi.org/10.1016/j.conbuildmat.2020.118147.
1286	[87]	H. Xu, J.S.J. Van Deventer, Effect of source materials on geopolymerization, Ind. Eng. Chem.
1287		Res. 42 (2003) 1698–1706. https://doi.org/10.1021/ie0206958.
1288	[88]	J. Li, M. Hitch, Mechanical activation of magnesium silicates for mineral carbonation , a review,
1289		Miner. Eng. 128 (2018) 69–83. https://doi.org/10.1016/j.mineng.2018.08.034.
1290	[89]	I. Tole, K. Habermehl-Cwirzen, A. Cwirzen, Mechanochemical activation of natural clay
1291		minerals: an alternative to produce sustainable cementitious binders – review, Mineral. Petrol.
1292		113 (2019). https://doi.org/10.1007/s00710-019-00666-y.
1293	[90]	F. Pacheco-Torgal, J.A. Labrincha, C. Leonelli, A. Palomo, P. Chindaprasirt, Handbook of
1294		Alkali-Activated Cements, Mortars and Concretes, 2014. https://doi.org/10.1016/C2013-0-
1295		16511-7.
1296	[91]	F. Vargas, M. Lopez, Development of a new supplementary cementitious material from the
1297		activation of copper tailings: Mechanical performance and analysis of factors, J. Clean. Prod.
1298		182 (2018) 427–436. https://doi.org/10.1016/j.jclepro.2018.01.223.
1299	[92]	R. Fernandez, F. Martirena, K.L. Scrivener, The origin of the pozzolanic activity of calcined
1300		clay minerals: A comparison between kaolinite, illite and montmorillonite, Cem. Concr. Res. 41
1301		(2011) 113–122. https://doi.org/10.1016/j.cemconres.2010.09.013.
1302	[93]	D. Feng, J.L. Provis, J.S.J. Van Deventer, Thermal activation of albite for the synthesis of one-
1303		part mix geopolymers, J. Am. Ceram. Soc. 95 (2012) 565–572. https://doi.org/10.1111/j.1551-
1304		2916.2011.04925.x.
1305	[94]	N. Sedira, J. Castro-Gomes, Study of an alkali-activated binder based on tungsten mining mud
1306		and brick powder waste, MATEC Web Conf. 163 (2018) 1–8.
1307		https://doi.org/10.1051/matecconf/201816306002.
1308	[95]	J. Kiventerä, J. Yliniemi, L. Golek, J. Deja, V. Ferreira, M. Illikainen, Utilization of sulphidic
1309		mine tailings in alkali-activated materials, MATEC Web Conf. 274 (2019) 01001.
1310		https://doi.org/10.1051/matecconf/201927401001.
1311	[96]	A. Mette, T. Simonsen, S. Solismaa, H.K. Hansen, P.E. Jensen, Evaluation of mine tailings '
1312		potential as supplementary cementitious materials based on chemical , mineralogical and
1313		physical characteristics, Waste Manag. 102 (2020) 710–721.
1314		https://doi.org/10.1016/j.wasman.2019.11.037.
1315	[97]	C. Yang, C. Cui, J. Qin, X. Cui, Characteristics of the fired bricks with low-silicon iron tailings,
1316		Constr. Build. Mater. 70 (2014) 36–42. https://doi.org/10.1016/j.conbuildmat.2014.07.075.
1317	[98]	N. Sedira, J. Castro-Gomes, M. Magrinho, Red clay brick and tungsten mining waste-based
1318		alkali-activated binder: Microstructural and mechanical properties, Constr. Build. Mater. 190
1319		(2018) 1034–1048. https://doi.org/10.1016/j.conbuildmat.2018.09.153.
1320	[99]	W. Liu, T. Wu, Z. Li, X. Hao, A. Lu, Preparation and characterization of ceramic substrate from
1321		tungsten mine tailings, Constr. Build. Mater. 77 (2015) 139–144.
1322		https://doi.org/10.1016/j.conbuildmat.2014.12.094.
1323	[100]	G. Young, M. Yang, Preparation and characterization of Portland cement clinker from iron ore
1324		tailings, Constr. Build. Mater. 197 (2019) 152–156.
1325		https://doi.org/10.1016/j.conbuildmat.2018.11.236.
1326	[101]	A. Buchwald, M. Hohmann, K. Posern, E. Brendler, The suitability of thermally activated
1327		illite/smectite clay as raw material for geopolymer binders, Appl. Clay Sci. 46 (2009) 300–304.
1328		https://doi.org/10.1016/j.clay.2009.08.026.
1329	[102]	H. He, Q. Yue, Y. Qi, B. Gao, Y. Zhao, H. Yu, J. Li, Q. Li, Y. Wang, The effect of incorporation
1330		of red mud on the properties of clay ceramic bodies, Appl. Clay Sci. 70 (2012) 67–73.
1331		https://doi.org/10.1016/j.clay.2012.09.022.
1332	[103]	T.P. Chang, J.Y. Shih, K.M. Yang, T.C. Hsiao, Material properties of portland cement paste
1333		with nano-montmorillonite, J. Mater. Sci. 42 (2007) 7478–7487.
1334		https://doi.org/10.1007/s10853-006-1462-0.

1335 [104] F. Pacheco-Torgal, S. Jalali, Influence of sodium carbonate addition on the thermal reactivity
1336 of tungsten mine waste mud based binders, Constr. Build. Mater. 24 (2010) 56–60.
1337 https://doi.org/10.1016/j.conbuildmat.2009.08.018.
1338 [105] C.R. Kaze, G.L. Lecomte-Nana, E. Kamseu, P.S. Camacho, A.S. Yorkshire, J.L. Provis, M.
1339 Duttine, A. Wattiaux, U.C. Melo, Mechanical and physical properties of inorganic polymer
1340 cement made of iron-rich laterite and lateritic clay: A comparative study, Cem. Concr. Res. 140
1341 (2021). https://doi.org/10.1016/j.cemconres.2020.106320.
1342 [106] J.M. Franco de Carvalho, K. Defáveri, J.C. Mendes, W. Schmidt, H.C. Kühne, R.A.F. Peixoto,
1343 Influence of particle size-designed recycled mineral admixtures on the properties of cement-
1344 based composites, Constr. Build. Mater. 272 (2021).
1345 https://doi.org/10.1016/j.conbuildmat.2020.121640.
1346 [107] G. Yao, Q. Wang, Z. Wang, J. Wang, X. Lyu, Activation of hydration properties of iron ore
1347 tailings and their application as supplementary cementitious materials in cement, Powder
1348 Technol. 360 (2020) 863–871. https://doi.org/10.1016/j.powtec.2019.11.002.
1349 [108] M. Zbik, R.S.C. Smart, Influence of dry grinding on talc and kaolinite morphology: Inhibition of
1350 nano-bubble formation and improved dispersion, Miner. Eng. 18 (2005) 969–976.
1351 https://doi.org/10.1016/j.mineng.2005.01.005.
1352 [109] H. Niu, P. Kinnunen, H. Sreenivasan, E. Adesanya, M. Illikainen, Structural collapse in
1353 phlogopite mica-rich mine tailings induced by mechanochemical treatment and implications to
1354 alkali activation potential, Miner. Eng. 151 (2020) 106331.
1355 https://doi.org/10.1016/j.mineng.2020.106331.
1356 [110] G. Yao, Z. Wang, J. Yao, X. Cong, C. Anning, X. Lyu, Pozzolanic activity and hydration
1357 properties of feldspar after mechanical activation, Powder Technol. 383 (2021) 167–174.
1358 https://doi.org/10.1016/j.powtec.2021.01.042.
1359 [111] Y. Cheng, F. Huang, W. Li, R. Liu, G. Li, J. Wei, Test research on the effects of
1360 mechanochemically activated iron tailings on the compressive strength of concrete, Constr.
1361 Build. Mater. 118 (2016) 164–170. https://doi.org/10.1016/j.conbuildmat.2016.05.020.
1362 [112] P. Perumal, H. Niu, J. Kiventerä, P. Kinnunen, M. Illikainen, Upcycling of mechanically treated
1363 silicate mine tailings as alkali activated binders, Miner. Eng. 158 (2020) 106587.
1364 https://doi.org/10.1016/j.mineng.2020.106587.
1365 [113] A. Hajimohammadi, J.S.J. van Deventer, Dissolution behaviour of source materials for
1366 synthesis of geopolymer binders: A kinetic approach, Int. J. Miner. Process. 153 (2016) 80–86.
1367 https://doi.org/10.1016/j.minpro.2016.05.014.
1368 [114] H. Xu, J.S.J. Van Deventer, Geopolymerisation of multiple minerals, Miner. Eng. 15 (2002)
1369 1131–1139. https://doi.org/10.1016/S0892-6875(02)00255-8.
1370 [115] F. Pacheco-Torgal, J.P. Castro-Gomes, S. Jalali, Investigations on mix design of tungsten
1371 mine waste geopolymeric binder, Constr. Build. Mater. 22 (2008) 1939–1949.
1372 https://doi.org/10.1016/j.conbuildmat.2007.07.015.
1373 [116] P. Duxson, J.L. Provis, G.C. Lukey, S.W. Mallicoat, W.M. Kriven, J.S.J. Van Deventer,
1374 Understanding the relationship between geopolymer composition, microstructure and
1375 mechanical properties, Colloids Surfaces A Physicochem. Eng. Asp. 269 (2005) 47–58.
1376 https://doi.org/10.1016/j.colsurfa.2005.06.060.
1377 [117] Y.M. Liew, H. Kamarudin, A.M. Mustafa Al Bakri, M. Bnhussain, M. Luqman, I. Khairul Nizar,
1378 C.M. Ruzaidi, C.Y. Heah, Optimization of solids-to-liquid and alkali activator ratios of calcined
1379 kaolin geopolymeric powder, Constr. Build. Mater. 37 (2012) 440–451.
1380 https://doi.org/10.1016/j.conbuildmat.2012.07.075.
1381 [118] A. Fernandes, M. Magrinho, J. Castro-Gomes, Leaching of alkali-activated tungsten mining
1382 waste materials by electrical conductivity and DRX, MATEC Web Conf. 274 (2019) 02002.
1383 https://doi.org/10.1051/matecconf/201927402002.
1384 [119] J. Kiventerä, I. Lancellotti, M. Catauro, F.D. Poggetto, C. Leonelli, M. Illikainen, Alkali
1385 activation as new option for gold mine tailings inertization, J. Clean. Prod. 187 (2018) 76–84.
1386 https://doi.org/10.1016/j.jclepro.2018.03.182.
1387 [120] A. Peys, A.P. Douvalis, V. Hallet, H. Rahier, B. Blanpain, Y. Pontikes, Inorganic Polymers
1388 From CaO-FeOx-SiO2 Slag: The Start of Oxidation of Fe and the Formation of a Mixed
1389 Valence Binder, Front. Mater. 6 (2019) 1–10. https://doi.org/10.3389/fmats.2019.00212.
1390 [121] R. Obenaus-Emler, M. Falah, M. Illikainen, Assessment of mine tailings as precursors for
1391 alkali-activated materials for on-site applications, Constr. Build. Mater. 246 (2020) 118470.
1392 https://doi.org/10.1016/j.conbuildmat.2020.118470.
1393 [122] S.A. Bernal, E.D. Rodríguez, A.P. Kirchheim, J.L. Provis, Management and valorisation of
1394 wastes through use in producing alkali-activated cement materials, J. Chem. Technol.

1395   Biotechnol. 91 (2016) 2365–2388. https://doi.org/10.1002/jctb.4927.

1396 [123] N. Sedira, J. Castro-Gomes, Effect of activators on hybrid alkaline binder based on tungsten
1397   mining waste and ground granulated blast furnace slag, Constr. Build. Mater. 232 (2020)
1398   117176. https://doi.org/10.1016/j.conbuildmat.2019.117176.

1399 [124] P.H.R. Borges, F.C.R. Ramos, T.R. Caetano, T.H. Panzerra, H. Santos, Reuse of iron ore
1400   tailings in the production of geopolymer mortars, Rev. Esc. Minas. 72 (2019) 581–587.
1401   https://doi.org/10.1590/0370-44672017720169.

1402 [125] K. doCarmoeSilvaDefáveri, L. dosSantos, R.A.F. Peixoto, G.J. Brigolini, J. FrancodeCarvalho,
1403   K. do Carmo e Silva Defáveri, L.F. dos Santos, J.M. Franco de Carvalho, R.A.F. Peixoto, G.J.
1404   Brigolini, Iron ore tailing-based geopolymer containing glass wool residue: A study of
1405   mechanical and microstructural properties, Constr. Build. Mater. 220 (2019) 375–385.
1406   https://doi.org/10.1016/j.conbuildmat.2019.05.181.

1407 [126] A. Wang, H. Liu, X. Hao, Y. Wang, X. Liu, Z. Li, Geopolymer synthesis using garnet tailings
1408   from molybdenum mines, Minerals. 9 (2019). https://doi.org/10.3390/min9010048.

1409 [127] C.R. Wu, Z.Q. Hong, Y.H. Yin, S.C. Kou, Mechanical activated waste magnetite tailing as
1410   pozzolanic material substitute for cement in the preparation of cement products, Constr. Build.
1411   Mater. 252 (2020) 119129. https://doi.org/10.1016/j.conbuildmat.2020.119129.

1412 [128] S. Liu, L. Wang, Q. Li, J. Song, Hydration properties of Portland cement-copper tailing powder
1413   composite binder, Constr. Build. Mater. 251 (2020) 118882.
1414   https://doi.org/10.1016/j.conbuildmat.2020.118882.

1415 [129] F. Rao, Q. Liu, Geopolymerization and its potential application in mine tailings consolidation: A
1416   review, Miner. Process. Extr. Metall. Rev. 36 (2015) 399–409.
1417   https://doi.org/10.1080/08827508.2015.1055625.

1418 [130] J. Kiventerä, L. Golek, J. Yliniemi, V. Ferreira, J. Deja, M. Illikainen, Utilization of sulphidic
1419   tailings from gold mine as a raw material in geopolymerization, Int. J. Miner. Process. 149
1420   (2016) 104–110. https://doi.org/10.1016/j.minpro.2016.02.012.

1421 [131] P. Perumal, K. Piekkari, H. Sreenivasan, P. Kinnunen, M. Illikainen, One-part geopolymers
1422   from mining residues – Effect of thermal treatment on three different tailings, Miner. Eng. 144
1423   (2019) 106026. https://doi.org/10.1016/j.mineng.2019.106026.

1424 [132] B. Malagón, G. Fernández, J.M. De Luis, R. Rodríguez, Feasibility study on the utilization of
1425   coal mining waste for Portland clinker production, Environ. Sci. Pollut. Res. 27 (2020) 21–32.
1426   https://doi.org/10.1007/s11356-019-05150-w.

1427 [133] S. Siddique, J.G. Jang, Assessment of molybdenum mine tailings as filler in cement mortar, J.
1428   Build. Eng. 31 (2020) 101322. https://doi.org/10.1016/j.jobe.2020.101322.

1429 [134] I. Vegas, M. Cano, I. Arribas, M. Frías, O. Rodríguez, Physical-mechanical behavior of binary
1430   cements blended with thermally activated coal mining waste, Constr. Build. Mater. 99 (2015)
1431   169–174. https://doi.org/10.1016/j.conbuildmat.2015.07.189.

1432 [135] X. Jiao, Y. Zhang, T. Chen, S. Bao, T. Liu, J. Huang, Geopolymerisation of a silica-rich tailing,
1433   Miner. Eng. 24 (2011) 1710–1712. https://doi.org/10.1016/j.mineng.2011.09.008.

1434 [136] R.A.M. Figueiredo, P.R.G. Brandão, M. Soutsos, A.B. Henriques, A. Fourie, D.B. Mazzinghy,
1435   Producing sodium silicate powder from iron ore tailings for use as an activator in one-part
1436   geopolymer binders, Mater. Lett. 288 (2021) 129333.
1437   https://doi.org/10.1016/j.matlet.2021.129333.

1438 [137] X. Liu, N. Zhang, H. Sun, J. Zhang, L. Li, Structural investigation relating to the cementitious
1439   activity of bauxite residue - Red mud, Cem. Concr. Res. 41 (2011) 847–853.
1440   https://doi.org/10.1016/j.cemconres.2011.04.004.

1441 [138] S. Jian, W. Gao, Y. Lv, H. Tan, X. Li, B. Li, W. Huang, Potential utilization of copper tailings in
1442   the preparation of low heat cement clinker, Constr. Build. Mater. 252 (2020) 119130.
1443   https://doi.org/10.1016/j.conbuildmat.2020.119130.

1444 [139] S. Ahmari, L. Zhang, Durability and leaching behavior of mine tailings-based geopolymer
1445   bricks, Constr. Build. Mater. 44 (2013) 743–750.
1446   https://doi.org/10.1016/j.conbuildmat.2013.03.075.

1447 [140] M. Falah, K. Ohenoja, R. Obenaus-Emler, P. Kinnunen, M. Illikainen, Improvement of
1448   mechanical strength of alkali-activated materials using micro low-alumina mine tailings, Constr.
1449   Build. Mater. 248 (2020) 118659. https://doi.org/10.1016/j.conbuildmat.2020.118659.

1450 [141] L. Caneda-Martínez, J. Sánchez, C. Medina, M. Isabel Sánchez de Rojas, J. Torres, M. Frías,
1451   Reuse of coal mining waste to lengthen the service life of cementitious matrices, Cem. Concr.
1452   Compos. 99 (2019) 72–79. https://doi.org/10.1016/j.cemconcomp.2019.03.007.

1453 [142] EPA Guidelines, TOXICITY CHARACTERISTIC LEACHING PROCEDURE, Method 1311, 148
1454   (n.d.) 148–162.

1455 [143] EUROPEAN COMMISSION, Commission notice on technical guidance on the classification of
1456 waste, Off. J. Eur. Union. C 124 (2018) 134.
1457 [144] J.P. Castro-Gomes, A.P. Silva, R.P. Cano, J. Durán Suarez, A. Albuquerque, Potential for
1458 reuse of tungsten mining waste-rock in technical-artistic value added products, J. Clean. Prod.
1459 25 (2012) 34–41. https://doi.org/10.1016/j.jclepro.2011.11.064.
1460 [145] J. Nouairi, W. Hajjaji, C.S. Costa, L. Senff, C. Patinha, E. Ferreira da Silva, J.A. Labrincha, F.
1461 Rocha, M. Medhioub, Study of Zn-Pb ore tailings and their potential in cement technology, J.
1462 African Earth Sci. 139 (2018) 165–172. https://doi.org/10.1016/j.jafrearsci.2017.11.004.
1463 [146] C. Reichl, M. Schatz, World Mining Data 2021, Vienna, 2021.
1464 [147] Responsible Mining Foundation, Responsible Mining Index Methodology 2020, (2020) 138.
1465 https://www.responsibleminingfoundation.org/app/uploads/RMI_Methodology2020_EN.pdf.
1466 [148] Near-zero-waste recycling of low-grade sulphidic mining waste for critical-metal, mineral and
1467 construction raw-material production in a circular economy, (n.d.). https://h2020-nemo.eu/
1468 (accessed September 15, 2021).
1469
1470