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Mine tailings-based geopolymers: A comprehensive review

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ABSTRACT

The mining industry produces a large amount of stone waste and tailings, which poses a threat to the environment. Dumping is the most common means of disposing of this industrial waste, contributing to soil degradation and water pollution with the acquisition of valuable land. Fortunately, it can be recycled in a variety of technologies, including the promising geopolymerization technology, which turns waste into value. This review paper presents recent advances in the production of mine tailings-based geopolymer composites from industrial waste as a potential sustainable building material. This article also provides in-depth studies on the behaviors and characteristics of mine tailings composites utilized in geopolymer production, such as physical properties, mechanical properties, durability properties, microstructural properties, thermal properties, leaching behavior, and potential applications. Besides, study developments are moving towards a comprehensive understanding of the environmental footprints and economic benefits of mine tailings-based geopolymer composites for building applications utilizing mine tailings as suitable concrete material. This review paper also highlights knowledge gaps that must be overcome to progress mine tailings composites for geopolymers, as well as future study opportunities based on prior research and existing challenges.

1. Introduction

Mine tailings accumulate in tailings ponds and mine waste landfills, and the challenge of sustainable disposal of these wastes is becoming considerably more critical [1–7]. This is due to the metallurgical and mining sectors' increasing production volumes, as well as the lack of an acceptable means for disposing of the waste created by these industries, on the one hand. On the other hand, it can be explained by the increasing stringency of ecological regulations in the majority of wealthy countries throughout the world. Lead and mercury, radioactive materials, and other mine tailings-related toxins are actively released into the environment as a result of the buildup of tailings [8–11], biota [12–19], polluting soils, air [20–25], and water [26–31], and causing cancer in humans [32–40]. Pollutants from food processing and feed waste harm valuable farms and natural ecosystems [41–45]. The functioning of tailing dams increases the likelihood of man-made catastrophes occurring [18,46–53].

Furthermore, from the standpoint of rational natural resource management, mine tailings should be seen as a mineral source that has been extracted from the earth's subsurface, transported, and underutilized. The tailings can comprise trace amounts of target material as well as previously unclaimed elements that can be restored via more effective mining procedures [46,54–58], which is one reason for this viewpoint. The chemical composition of mine tailings, on the other hand, is primarily composed of silicon, aluminum, and calcium oxides, with a percentage ranging from 60 to 90% [59–62]. As a result, tailings have the potential to serve as an alternative source for meeting a wide range of construction and industry requirements [25,46,63–78].

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A prospective trend in mine tailings use appears to be the use of mine tailings as geopolymers and precursors of alkali-activated materials or aggregates [79–86]. Materials composed mostly of amorphous sodium aluminum-silicate hydrate are called geopolymers [87]. They are primarily solids formed by the interaction of an aluminosilicate powder and an alkali solution [88]. According to van Deventer, Provis, Duxson and Brice [87], the geopolymer network is composed of AlO_4 and SiO_4 tetrahedra connected by oxygen atoms [88]; Positively charged ions (e.g., Ca_2^+, Na^+, K^+, and Li^+) present in the cavity framework balance the negative charge. It is possible that using mine tailings as a geopolymer approach will not only slow down the accumulation of mine tailings and reduce the level of ecological contamination, but it will also combine the benefits of geopolymer technology associated with a reduction in carbon dioxide release into the environment, the potential of utilizing other forms of aluminosilicate waste, and the versatility of geopolymer characteristics as a general-purpose construction adhesion [89–93]. Recently, there has been a considerable increase in understanding among a diverse group of specialists in the management of tails in common methods. Over a dozen articles have been published detailing the efforts made to increase our understanding of the geopolymerization processes of tails in order to govern the properties of geopolymers for applications such as pollutant removal [94–96], sustainable building [70,71,97–99], and another particular usage [34,70,98,100–108].

The mine tailings are inhomogeneous and have a complex mineral, aggregate, and chemical composition [59,109–111]. Furthermore, although having relatively low quantities of valuable components, mine tailings contain hazardous and toxic compounds connected with waste products or mining activities [82,84,112–114]. All of these factors make it more difficult to manage mine tailings directly in order to obtain geopolymers that meet ecological safety criteria in respect of impurity content while also achieving the essential complex functional characteristics for the manufactured product.

As a result, tackling the issues associated with the use of mine tailings-geopolymer composites is especially useful, both in terms of limiting the negative impact on the environment and the prospect of growing the resource base of fabricated mineral raw materials. It is greatly beneficial to solve the problems linked with the use of mine tailings-geopolymer composites. This review begins with a discussion of some of the physicochemical and ecological issues surrounding the utilization of mine tailings-geopolymer composites. Mine tailings-geopolymer composites are discussed in length in this paper, which is both a generalization and a thorough investigation of the link between their structural, mechanical, and thermal capabilities, as well as their durability and other substantial aspects. Apart from the useful features of the formation of the characteristics of mine tailings-geopolymer composites, we discuss comprehensively the well-known cases of its utilization in promising applications.

2. Geopolymerization

Geopolymer is an amorphous aluminosilicate that results from the polycondensation of inorganic compounds [115,116]. It is defined as an alkali-activated material and is produced through the reaction of aluminosilicate materials with an alkaline activator, which is usually a concentrated alkali hydroxide, silicate, carbonate, or sulfate. In the late 1970s, Professor Joseph Davidovits carried out research on fireproof polymers and introduced the term geopolymer, which was coined to describe a family of alkali-activated aluminosilicate binders [115,116]. Once oversaturation is attained, the raw material dissolves in an alkaline solution, generating Si and Al molecules that produce gels. Subsequent restructuring and polycondensation result in the creation of a stiff three-dimensional network composed of $Si_4^+ O_4$ and $Al_3^+ O_4$ tetrahedrons linked by oxygen bridges [117–121]. Alkali metal cations equalize the charge of Al_3^+. Fig. 1 shows, in simplified form, the geopolymerization process. RM is very alkaline and composed of aluminosilicates, making it an ideal source for the creation of geopolymers. In the past, mine tailings have been used as a geopolymer binder with a variety of different mineral compounds, such as fly ash, rice husk ash, slag, municipal solid waste, metakaolin, arsenic sludge, and coal gangue [35,122–124].

3. Mine tailings

3.1. Characteristics

Mine tailing particles are angular, resulting in a high friction angle of dry tailings. Their size varies greatly and is difficult to generalize because it depends on the mineral processing requirements. Froth flotation separates minerals from the gangue by capitalizing on their hydrophobicity difference, which requires fine silt-size particles (normally, 300–50 μm) [126]. Gravity concentration is another technique of separation; it focuses on the density difference between the heavier (sulfides) and lighter (silicates) components and employs a bigger

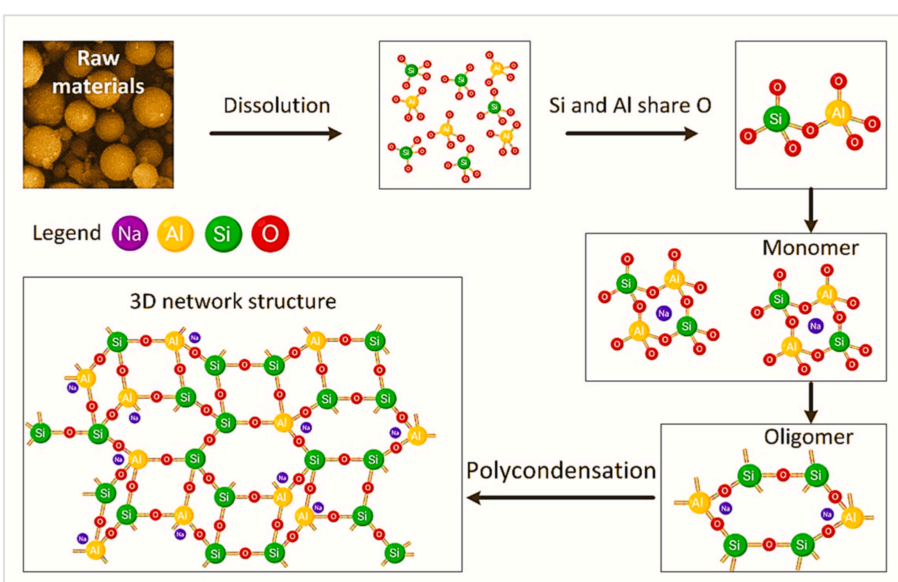


Fig. 1. Simplified Geopolymerization Process [125].

particle size (about 1 mm) [127]. The mine tailings that are made with the froth flotation method have smaller particles, which makes them more likely to let out contaminants [128].

The mineralogy of mine tailings is strongly dependent on the type of the raw ore, the mineral processing technology, and the degree of weathering during storage in tailings ponds [129]. The most common gangue constituents are quartz, feldspars, muscovite, chlorite (($(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2(OH)_6$), calcite, and dolomite [129]. The most frequent sulfide minerals found in ores include pyrite, pyrrhotite, chalcopyrite, arsenopyrite, sphalerite, and galena, which are likely to be found in mine tailings. Such sulfide-containing mining tailings are prone to oxidation during weathering, releasing hazardous metals and metalloids, including As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn [130]. The secondary minerals that form in the mine tailings, like iron hydroxide, iron oxyhydroxide, goethite, lepidocrocite, jarosite, schwertmannite, and ferrihydrite, precipitate and stay in the tailings [131].

The alkali solubility of silicon and aluminum impacts the reactivity of possible geopolymerization precursors, which is determined by their mineralogy. As a result, the reactivity of mine tailings can be generally estimated based on their mineralogical features. Xu and Van Deventer [132] studied the behavior of 16 natural Al–Si minerals in terms of geopolymerization (almandine, grossular, sillimanite, andalusite, kyanite, pumpellyite, spodumene, augite, lepidolite, illite, calcian, sodalite, hydroxy apophyllite, stilbite, heulandite, and anorthite). All of the minerals were soluble to some extent in concentrated alkaline solutions; the framework structure showed greater dissolution than other structures for both Si and Al, with chain structures being the next most soluble. According to the report by Ouffa, Benzaazoua, Belem, Trauchessec and Lecomte [100], the greatest dissolving rates are seen in phyllosilicates such as kaolinite, muscovite, chlorite, and biotite. Quartz, a common silicate found in mine tailings, dissolves at a rate that is not exceedingly small in alkaline solutions, which helps make geopolymers strong over time.

3.2. Physical and chemical properties of mine tailings

In the mining industry, mine tailings are a fine-grained blend of ground-up stone particles and processing effluents created as a byproduct of the extraction of precious minerals and metals from mined ore [70,83,129,133–138]. During the process of ore beneficiation, more than half of the overall ore bulk is converted into tailings.

The consistency of mine tailings can change significantly depending on the kind of beneficiation and storage utilized—from a slurry condition to a thicker paste state and finally to a dry state, depending on the technique of storage and beneficiation used. The solid content of each of these types can range from 15 to 86% or more, depending on the types listed in Table 1. Typically, geopolymers are typically made from dried tails, which can be obtained either by dry preparation techniques or by sintering [95,138,139].

Mine tailings used in geopolymers are primarily composed of a combination of mineral particles of diverse sizes – ranging from silt and clay fractions to heavy sandy fractions – with varying degrees of agglomeration. In addition to grinding procedures and mineral processing technologies, the hardness of the minerals included in stones affects the particle size distribution of tails, as demonstrated by Sternal, Junttila, Skirbekk, Forwick, Carroll and Pedersen [140], Duan, Yan, Zhou and Ren [141], and Cao, Wang, Yin and Wei [142]. In general, the particle form of most tailings is non-rounded, angular, and irregular, which is the consequence of crushing and grinding throughout the ore processing process. The specific surface area of mine tailings, which ranges between 0.5 and 7.3 m^2/g and is impacted by the distribution and particle shape, is measured [142].

The bulk density of mine tailings in the bulk state ranges from 1.81 to 1.93 t/m^3, with 1.81 t/m^3 being the average value. These values increase in proportion to the depth of the mine tailings or dumps in question [129,143,144]. It has been demonstrated that the density of tailings changes depending on the type of mineral raw material utilized [145]. Because its pH differs from that of the parent mineral, mine tailings can fall into either the acidic or basic ranges.

As shown in Tables 2 and 3, the mine tailings used in the fabrication of geopolymers have a considerable degree of inhomogeneity in their properties. Because of the ore's characteristics, the type of process fluids (surfactants and other reagents) used in the beneficiation process, the degree of mining of a target substance, and physical and chemical modifications that occur during mine tailings storage, the chemical composition of tailings varies. As demonstrated in Table 2 and Fig. 2, the major chemicals in mine tailings in all instances are Al_2O_3, SiO_2, Fe_2O_3, CaO, MgO, Na_2O, and K_2O.

As demonstrated in Table 2, the chemical composition of mine tailings is distinguished by a wide variation of values for some components, even within the same mine. The observed variation in chemical and mineral composition is most likely caused by the intrinsic inhomogeneity of the host stone that houses the ore deposit. This should also be considered while putting together the final composition of the geopolymer.

3.3. Environmental consequences and waste disposal

The disposal of mine tailings is one of the most substantial causes of ecological damage caused by the mining industry. This is not surprising given the fact that the amount of mine tailings that must be kept often surpasses the amount of ore that can be extracted in situ. Mine tailings have increased significantly over the last century as a result of increased demand for metals and minerals, as well as the adoption of better mining and processing processes to utilize low-grade minerals and extract more value from them. A recent report published by the Chinese Academy of Land and Resources Economics estimates that China's mining tailings pile stock was around 21 billion tons at the end of 2018. If mine waste is not properly disposed of, it may lead to serious ecological consequences like acid mine drainage, dust mobilization, heavy metal buildup in biological communities, and soil contamination as shown in Fig. 3.

As a result of this ecological load, it is essential to dispose of mine tailings in a fair manner, as shown in Fig. 4. A substantial portion of the past research has concentrated on the recycling of main tailings as a backfill cement paste [67]. Surface mine tailings are often combined with a binder in a small backfill factory before being transferred to subterranean stopes through gravity and/or pumping [175]. The amount of mining tailings that must be kept in tailings ponds is lessened as a result of this method [175]. It is possible to decrease the challenges associated with mine tailings, such as dust generation, landslides, surface water pollution, and mine tailings occupying cultivated land. Important components can also be recovered from previously deposited mine tailings; for example, silver and lithium-containing minerals can be recovered from gold and micaceous tailings, respectively. Many forms of mine tailings have the potential for recycling and re-use, including Mn-rich tailings, which can be utilized to manufacture building materials, ceramics, glass, and coatings; clay-rich tailings, which can be

Table 1
Overview of the physical properties of mine tailings that have been reported in the literature [94,129,136,146–155].

Characteristic type		Value
Specific gravity (g/cm^3)		2.60–2.95
Density (t/m^3)		1.80–1.95
Solids bulk content (%)	Thickened tailings	46–75
	Tailing's slurry	15–36
	Dehydrated tailings	<84
	Paste tailings	72–86
Surface Area (m^2/g)		0.50–7.20
Porosity (%)		35–45
pH		2.60–2.95
Particle size distribution (μm)		1-2000

Table 2
The chemical compositions of various mine tailings that are utilized to produce geopolymers.

mine tailings type	Country	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	V_2O_3	V_2O_5	SO_2	TiO_2	SO_3	ZnO	MnO	CuO	BaO	PbO	LOIa	Others	Refs
Copper	China	28.20	57.83	4.25	1.91	1.15	0.52	0.80	–	–	–	–	0.32	–	–	–	–	–	–	–	–	[157]
	China	58.5	10.8	13.3	5.4	1.9	2.8	4.0	–	–	–	–	–	0.6	–	–	–	–	–	–	–	[149]
	USA	55.8	3.07	14.11	2.27	1.77	3.02	3.88	0.19	–	–	2.26	0.50	–	–	0.067	–	–	–	–	–	[158]
	USA	64.8	4.33	7.08	7.52	4.06	0.9	3.26	–	–	–	–	–	1.66	–	–	–	–	–	–	–	[86]
	Africa	65.48	8.07	12.08	5.91	2.85	1.23	0.55	0.12	–	0.04	–	0. 88	–	–	0.07	0.09	–	–	3.52	0.07	[159]
Gold	Africa	74.6	7.03	6.98	0.54	5.16	0.28	1.26	0.09	–	0.03	–	0.45	3.05	0.03	0.06	0.02	0.08	0.03	–	0.42	[160]
	Africa	63.8	16.2	5.5	3.2	4.3	1.2	0.6	0.1	–	0.01	–	0.3	–	–	0.1	$<$0.01	–	–	4.8	0.13	[159]
	Turkey	89.22	0.84	6.2	–	0.29	–	1.24	–	–	–	–	–	0.09	–	–	–	–	–	–	–	[95]
	Finland	49.9	9.2	10.4	11.8	6.8	–	1.2	–	–	–	–	1.2	–	–	–	–	–	–	13.6	–	[161]
Iron	Brazil	40.0	48.9	8.7	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6.0	1.8	[139]
	China	34.72	12.32	16.22	7.64	8.92	0.55	1.52	–	–	–	–	0.30	–	–	0.13	–	–	–	13.1 8	–	[136]
	Australia	57.30	25.12	9.57	0.03	0.07	0.05	0.04	–	–	–	–	0.61	0.16	–	–	–	–	–	6.67	–	[148]
Phosphate	Finland	32.98	7.98	7.08	12.92	17.28	–	5.53	0.96	–	–	–	0. 27	–	–	0.12	–	–	–	14.0 1	0.88	[162]
	Morocco	23.5	1.53	3.55	31.12	4.16	0.54	0.46	14.1	–	–	–	–	–	–	–	–	–	–	19.3	–	[97]
	Morocco	22.8	0.85	2.5	34.3	4.1	0.9	0.4	14.0	–	–	–	–	–	–	–	–	–	–	19	–	[163]
Vanadium	China	83.47	2.42	5.09	0.96	0.65	3.25	0.66	–	0.23	–	–	–	–	–	–	–	–	–	1.25	–	[164]
	China	61.92	4.13	7.35	6.52	1.24	2.68	1.25	–	–	0.42	–	0.46	7.15	–	–	–	–	–	6.93	–	[150]
	China	64.17	4.99	10.27	4.48	–	5.27	2.07	–	–	0.14	–	–	–	–	–	–	–	–	1.15	–	[165]
Kaolinite	Finland	72.55	1.90	16.44	0.05	0.83	0.08	3.06	–	–	–	–	–	–	–	–	–	–	–	4.42	0.74	[166]
Lead-zinc	China	62.09	2.73	4.35	20.45	0.56	–	0.55	–	–	–	–	0.20	3.63	–	–	–	–	–	–	–	[67]
Garnet	China	44.28	13.82	5.57	30.26	0.81	0.23	0.13	–	–	–	–	–	–	–	–	–	–	–	–	–	[167]
Lithium	Finland	78.45	0.51	12.56	0.30	0.15	4.44	2.81	–	–	–	–	–	–	–	–	–	–	–	0.20	0.58	[166]
Bauxite	China	32.25	8.66	37.39	3.16	0.85	0.86	–	–	–	–	–	2.31	–	–	–	–	–	–	13.74	–	[133]
Hematite	USA	68.77	28.13	0.87	0.28	0.74	0.03	0.04	–	–	–	–	0.05	–	–	–	0.001	0.02	–	–	0.07	[168]
Quartz	China	97.48	0.30	1.11	0.17	0.22	0.04	0.02	–	–	–	–	–	–	–	–	–	–	–	–	–	[169]
Sphalerite	China	6.22	0.18	2.06	33.65	9.94	0.32	0.24	0.27	–	–	–	0.09	1.43	1.75	–	–	0.31	0.15	43.65	–	[170]
Tungsten	Portugal	47.85	9.97	21.07	0.85	1.01	1.32	4.12	–	–	–	–	0.66	8.73	–	–	–	–	–	–	–	[171]
Zinc	China	38.4	11.8	12.65	29.8	–	–	1.65	0.84	–	–	–	0.59	0.52	2.96	0.62	0.21	–	0.23	–	0.12	[170]

Table 3
The mineralogical composition of various mine tailings utilized in the production of geopolymers.

Tailing types	Country	Mineralogical components (%)	Refs
Copper	South Africa	Chlorite (13.2), calcite (1.65), hematite (1.14), epidote (22.7), muscovite (4.7), hornblende (3.25), quartz (49.55), plagioclase (7.60)	[159]
	USA	Not reported	[172]
	China	Not reported	[149]
	China	Not reported	[173]
Gold	South Africa	Chlorite (2.95), anthophyllite (6.0), jarosite (7.70), hornblende (14.10), plagioclase (13.25), magnetite (3.65), sepiolite (9.35), quartz (42.95)	[159]
	Finland	Not reported	[159]
	South Africa	Not reported	[160]
Phosphate	Morocco	Quartz (12.5), fluorapatite (34.1), calcite (11.16), dolomite (9.46), kaolinite (9.45), hematite (1.5), plagioclase (21.2)	[97]
	Morocco	Quartz (18), fluorapatite (45), calcite (16), dolomite (72)	[83]
	Finland	Calcite (15), dolomite (5.95), feldspar (1.5), phlogopite (64), albite (0.98), actinolite (1.0)	[166]
	Finland	Calcite (13), dolomite (7), tremolite (1.5), phlogopite (65)	[162]
Iron	China	Not reported	[174]
	Brazil	Not reported	[139]
Kaolinite	Finland	Quartz (28), kaolinite (20.5), muscovite (43),	[166]
Sphalerite	China	Dolomite (45.70), quartz (3.70), kaolinite (5.20), calcite (35.25)	[170]
Garnet	China	Not reported	[167]
Lithium	Finland	Albite (38), quartz (37), microcline (15.8), muscovite (6.5), plagioclase (1.3), spodumene (2.7)	[166]
Vanadium	China	Not reported	[150]
Tungsten	Portugal	Not reported	[171]
Bauxite	China	Not reported	[133]

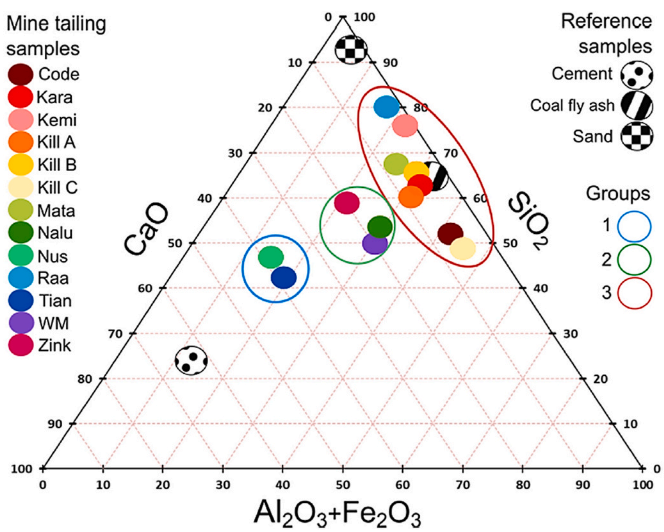


Fig. 2. Ternary phase diagram of the chemical composition of mine tailings and each of cement, coal fly ash, and sand [156].

utilized to manufacture bricks, sanitary wares, porcelain, and cement; iron ore tailings mixed with supplementary materials, like fly ash and sewage; bauxite-comprising tailings, which can be utilized as Al resources. These disposal techniques assist mining businesses in cleaning up existing mine tailings and converting them into something of value for the organizations. But any recycling or re-use of mine tailings needs a realistic evaluation of the pollutants that they may release. Consequently, complete knowledge of the geochemical, mineralogical, and bulk physical characteristics of mine tailings is required before they can be safely disposed of in the environment.

4. Economic and production perspective of mine tailings-geopolymer composites

Among the characteristics of the mining sector are a high use of energy resources and minerals, a low rate of mining of technically and economically relevant metals (between 1 and 4%), and a significant influence on the environment [177]. Some reports state that around 19–25 billion tons of solid mine waste are generated yearly across the globe, with 5–8 billion tons of mine tailings [146,178]. Furthermore, the expansion of the mining zone demands the creation of infrastructure to support extraction activities. As a result, mine tailings have become a valuable resource for the exploitation of sustainable construction materials such as geopolymers. Every two years, the number of publications grows by a factor of two [3,179], as well as a new resource for the production of metal that permits the resolution of both the economic and ecological issues associated with mine tailings disposal [180].

As shown in Fig. 5, the following is a review of the important production and economic concerns that should be considered while using mine tailings-geopolymer composites. Mine tailings-geopolymer composites are economically viable if the transportation costs paid by mine waste users are maintained at a low level. In this regard, significant consideration should be paid to the mining operation's geographic proximity to the prospective mine tailings clients as well as the regions of consumption of final geopolymer products. These features help to cut down on the costs of capital and operations for mine tailings development by about 44%, as well as the negative impact on the environment.

Mine tailings-geopolymer composites are economically efficient as compared to other substances because they lessen the amount of expenditures experienced by consumers of mine waste for transportation. The closeness of the mining firm to the targeted customers as well as the locations where finished geopolymer products will be consumed are critical considerations for the mining enterprise. These aspects help to lower the initial and operational expenses associated with the development of mine tailings.

5. Preparation and formation of mine tailings-based geopolymers

5.1. Effects of tailing types

As a precursor component for producing a geopolymer, any source of aluminosilicate raw materials can be used that provides the required concentration of dissolved aluminum and silicon-oxygen compounds that polymerize with the formation of a geopolymer structure during alkaline activation [181]. Microstructure and mechanical properties are affected by the ratio of liquid to solid, the ratio of SiO_2/Al_2O_3, and the ratio of Si/T (T = Na^+ or K^+), as well as the ratio of liquid to solid [182].

The heterogeneity of the chemical and mineral content of tailings formed in mining sites is an essential element influencing the phase composition and properties of geopolymers. The composition of the precursor is the decisive element in the creation of a geopolymer and its properties. From this point of view, the wide range of tailings properties

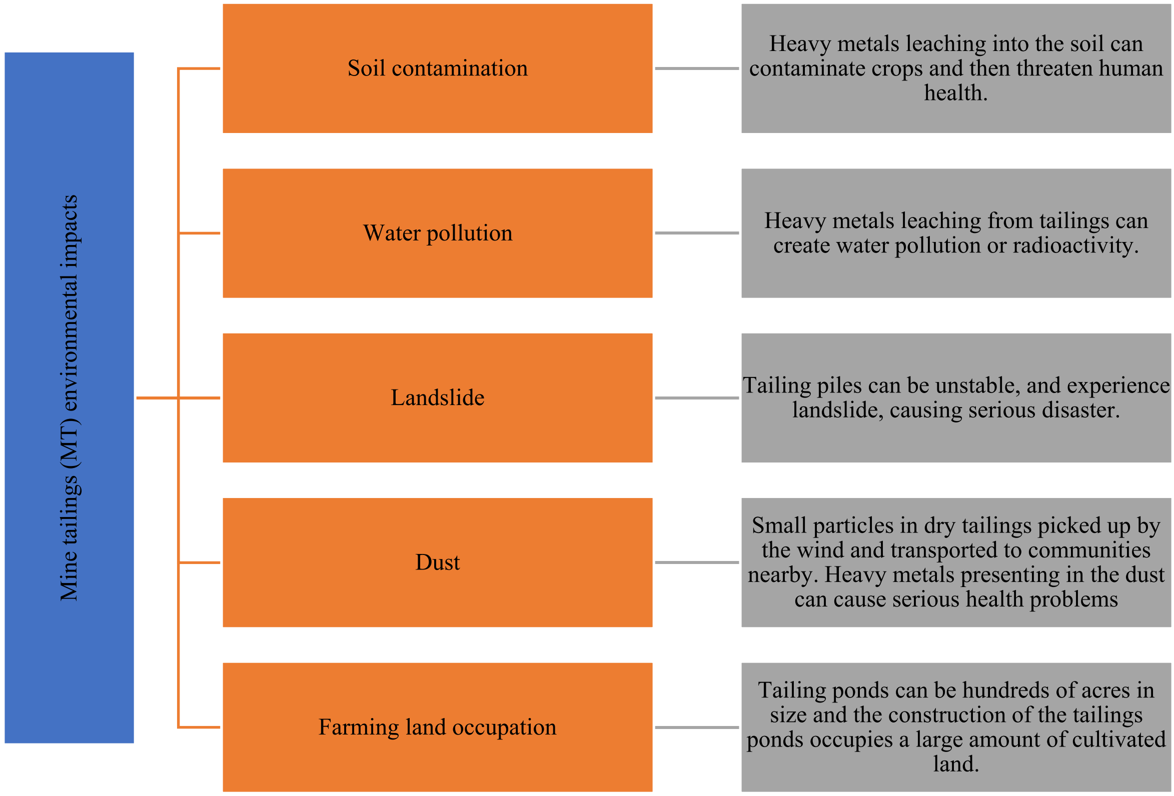


Fig. 3. Mine tailings environmental impacts [176].

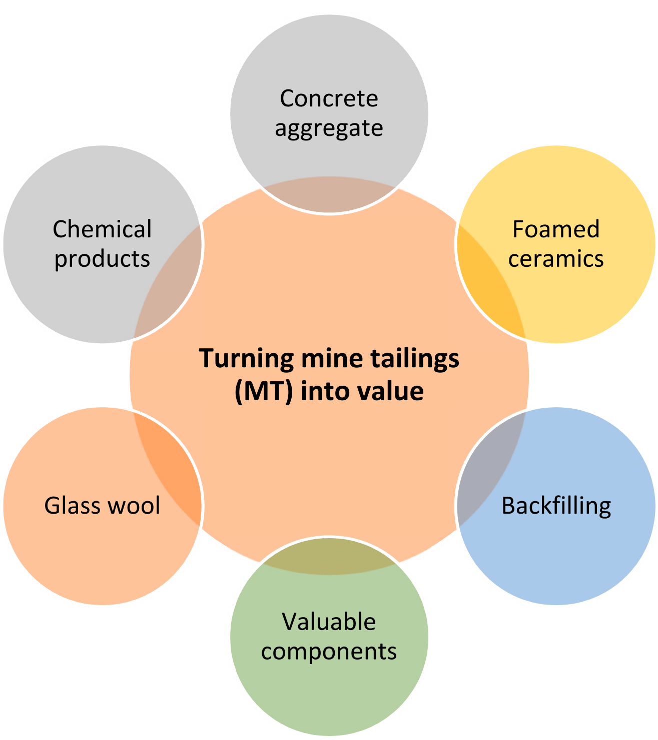


Fig. 4. Techniques for turning mine tailings into value [176].

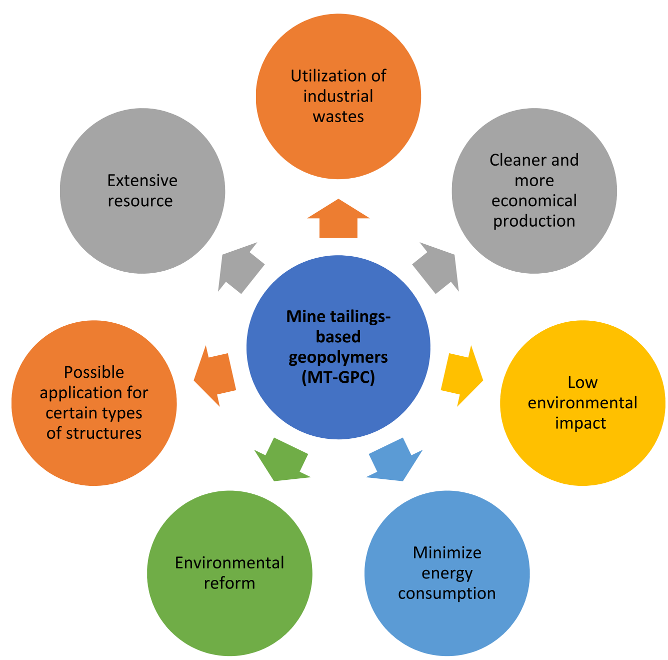


Fig. 5. Advantages of the utilization of mine tailings in geopolymers [59].

of different deposits is an important thing to think about when using mine tailings as a precursor to geopolymers.

The ability to employ tailings as a precursor to geopolymers depends on the nature of their pre-treatment. The geopolymerization of pretreated tailings is moderate compared to heat-treated materials such as metakaolin, slag, or fly ash. Their reactivity is determined by the preheat treatment, which results in amorphous and soluble phases. Pre-treatment makes the material more receptive, which leads to a faster rate of geopolymerization at the start and better mechanical properties when it is made into a material.

For example, an increase in the reactivity of mine tailings particles can be achieved by enlarging their surface area by bringing to the average particle size of the most reactive materials, for example, metakaolin (10 μm) [97]. Moreover, the average particle sizes for various mine tailings are the following: phosphate (40–160 μm) [83], vanadium (15–100 μm) [150], iron (19 77 μm) [139], sulfidic (12–100 μm) [179], zinc (20–50 μm) [183], copper (20 120 μm) [149]. In this case, pre-treatment, which reduces the particle size and broadens their surface area for alkaline dissolution, will enhance the involvement of mine tailings in the geopolymerization process of mineral components. Mechanical, thermal, and thermochemical pre-treatments can be used to make mine tailings more reactive, and they can all be used to do this.

Preliminary grinding is an effective procedure, which, depending on the time of exposure to mineral raw materials, can significantly extend the active surface area of an accessible alkaline medium and the dissolution rate of minerals. The resulting intense effect on the crystal structure of minerals destroys interatomic bonds, which leads to amorphization of the mineral phase. Niu, Abdulkareem, Sreenivasan, Kantola, Havukainen, Horttanainen, Telkki, Kinnunen and Illikainen [162] performed preliminary mechanical activation for phosphate mine tailings, consisting of the following predominant minerals: phlogopite, dolomite, calcite, and tremolite. It was shown that grinding in a brief period of time (16 min) ensured amorphization of up to 80% of the mineral phase with weakly expressed calcite crystallites according to X-ray diffraction data. A significant extension of the specific surface area by 87 times was observed. A similar effect was achieved in the work of Marjanović, Komljenović, Baščarević and Nikolić [184] for a 2:1-layer lattice mineral such as pyrophyllite. The energy during grinding, accumulating in the crystalline structure of minerals, breaks predominantly Al–O and Si–O bonds, transforming the mineral into an amorphous phase with the Al–Si structure. Preliminary grinding leads to a regular increase in the release concentrations of Si and Al with the predominance of the former upon alkaline activation of the precursor. Furthermore, due to the dissolution of the crystalline structure, there is a release of interlayer alkaline cations, providing compensation for the excess charge of the produced aluminosilicate structure. The release of increased quantities of Si and Al into the alkaline medium affects the Si/Al ratio, enhancing the involvement factor of the precursor's elemental structure in geopolymerization. As a control parameter, processing time allows you to vary the degree of amorphization of the minerals that make up the precursor, giving you control over the process of dissolving them in an alkaline solution. Wei, Zhang and Bao [150] demonstrated that this technique provides for control of the Si/Al ratio during geopolymerization. Mechanical activation of vanadium tails results in a change in the characteristic particle size (a 1.7-fold drop) and a specific surface area (it doubles). Increasing the reactivity of the precursor also speeds up the geopolymerization process, improves mechanical properties, and makes the material more resistant to chemicals.

5.2. Effects of pre-treatment

During thermal pre-treatment, the mineral components of the precursor are calcined. The characteristics of this treatment are related to the process of phase changes in the crystalline structure of minerals. Dihydroxylation occurs during the temperature rise process, with the loss of structural OH groups, primarily connected to aluminum atoms. This process enhances the local reactivity of aluminum atoms. Perumal, Piekkari, Sreenivasan, Kinnunen and Illikainen [166] studied three different mine tailings: phosphate, kaolinite, and lithium. A peculiarity of the thermos-phase transformations of the minerals that make up mine tailings is the possibility of a transition to a stable phase, which reduces reactivity. Thus, calcite (CaCO3) present in phosphate mine tailings, decomposing at a temperature of 750 °C, forms CaO. Further heat treatment leads to a phase transition to quartz, cordierite, and crystalline silicates at 900 °C with a decrease in reactivity. Moreover, the mineral composition of lithium mine tailings after heat treatment reduces reactivity. As a result, the use of heat treatment for mine tailings is restricted. Before using it, a detailed investigation of the mineral composition of mine tailings is necessary, which allows for the determination of the possibility of attaining the requisite reactivity by minerals.

Calcining the tails can enhance their pozzolanic activity, as evidenced by the work of Kotwica, Chorembała, Kapeluszna, Stępień, Deja, Illikainen and Gołek [185]. The long-term strength of alkali-activated materials can be improved by replacing some of the GBFS with tails like this.

The use of thermochemical synthesis makes it possible to increase the efficiency of thermal activation since a chemical reaction proceeds in the process of raising the temperature. In this case, low-reactive raw materials are thermally synthesized together with an activator before geopolymerization. Mine tailings are combined with sodium hydroxide to produce the desired result. The resultant material is calcined at a temperature higher than the melting point of alkali. Heat treatment in the presence of alkali disrupts the mineral's crystalline structure, resulting in the formation of new amorphous phases and crystalline structures saturated with Na. The thermochemical synthesis of volcanic ash carried out by Kouamo, Mbey, Elimbi, Diffo and Njopwouo [186] led to the transition of the predominant part of the containing minerals into a reactive form. The same effect is also observed in the work of Tchadjié, Djobo, Ranjbar, Tchakouté, Kenne, Elimbi and Njopwouo [187], where low-reactive granite waste using sodium hydroxide was applied. The key parameters of the thermochemical synthesis process are the calcination temperature and the amount of NaOH added to the molten system. Moreover, Na_2O can also affect the reactivity of the resulting product.

5.3. Effects of activator

The type of alkaline activator used, as well as its dose, have a crucial role in determining the rheological characteristics of the resulting aluminosilicate gel, as well as the structure and properties of the cured material. The most commonly used alkaline activators for mine tailings are solutions of sodium hydroxide and silicate, as well as their mixtures. KOH and K_2SiO_3 are much less commonly used. When the alkaline reaction is initiated, the activator balances the negatively infected aluminosilicate network with a charge of Na^+ or K^+ ions from the activator. Given the mineral composition of mine tailings, the optimal concentration of the alkaline solution can be selected. The Na/Al ratios defined by Manjarrez and Zhang [172] are in the following ranges for metakaolin, fly ash (1–1.15), copper (0.79–1.1), and aluminum (1.1) mine tailings. The activity of the alkaline medium also depends on the concentration of water molecules. A significant excess of the concentration of water molecules over Na^+ can lead to their diffusion from areas of uncompensated charge during geopolymerization. According to studies by Zhang, Zhou, Lin, Tong and Yu [188] and Ren, Zhang, Ramey, Waterman and Ormsby [189], the optimal ratio for the course of geopolymerization is Na/Al ~1.0. The estimation Si/Al≈3.31 performed by Manjarrez and Zhang [172] corresponds to the initial components of copper mine tailings/H_2O≈3.36. Moukannaa, Loutou, Benzaazoua, Vitola, Alami and Hakkou [83] studied the effect of various concentrations of NaOH on the formed structure of a geopolymer with phosphate sludge (PS). The prevalence of alkali-resistant quartz in the PS mineral composition reduces the amount of active silica, leading to the formation of a crystalline zeolite phase in the geopolymer structure due to the high molar ratio SiO_2/Al_2O_3. The sort of zeolite structure that forms in the geopolymer is affected by the concentration of NaOH. An increase in Na^+ concentration and temperature led to an increase in the density of the geopolymer structure.

5.4. Curing conditions

The studies indicate that the curing of the geopolymer with mine tailings included in its composition is carried out under conditions ranging from room temperature to 100 °C, which is also characteristic of geopolymers based on other aluminosilicate raw materials. Moukannaa, Loutou, Benzaazoua, Vitola, Alami and Hakkou [83] using phosphate mine tails, researchers investigated the curing regimes of a geopolymer based on metakaolin and fly ash, as well as the variables influencing this process. An increase in the concentration of NaOH or the curing temperature will limit water absorption. The buildup of cure time results in an increase in water absorption. An increase in the curing temperature has a beneficial effect on material compaction. The improvement of mechanical properties occurs with a rise in the concentration of NaOH and the curing temperature of the material. It was shown in the work by Jiao, Zhang and Chen [165] that the compressive strength and elastic modulus of a metakaolin-based geopolymer fall with rising curing temperature. The effect of curing temperature on the compressive strength and microstructure of copper mine tailings-based geopolymers was also investigated by Ozcan and Benzer [190]. According to their findings, a rise in the curing temperature from 25 to 80 °C promotes a more uniform distribution of C–S–H and N–A–S–H gels and intensifies the strength of the geopolymer. The temperature rose from 80 to 120 °C. This led to a drop in the geopolymer alkaline medium and a drop in the geopolymer compressive strength.

6. Physical properties

6.1. Workability

Workability of tailing-based composite concrete is the ease of working with the composite material based on transportation, compaction, placement, and finishing of the concrete product [191]. This means that the fresh property of tailing-based composite concrete can be regarded as workable if it can be transported, placed, compacted, and finished with ease and without any segregation. Several reports have shown that the flow of mortar decreases with an increase in tailing substitution levels since tailings have a finer particle size distribution, increasing the total specific surface area of the fine aggregates [192, 193], which is also applicable to concrete. Slump formation declines with increasing tailings substitution as fine aggregate, possibly due to surface texture and particle size of tailings, requiring more water, thereby reducing the workability [193,194]. The workability loss of geopolymer composite binders depends solely on the volume fraction in the mixtures and the fiber aspect ratio [195]. The report of Savastano Jr, Agopyan, Nolasco and Pimentel [196] reveals a decline in the workability of cement composites in the presence of eucalyptus pulp, coir, or eucalyptus pulp in combination with sisal fibers.

The workability of alkali-activated tailing paste is influenced by a combination of factors like calcination temperature and water-to-tailings ratio. Savastano Jr, Agopyan, Nolasco and Pimentel [196] reported that sufficient workability at 800 °C calcination requires water to waste clay containing a boron ratio of 0.40. For lower calcinations of 700 °C, 600 °C, and 500 °C, the required water to waste clay containing boron ratios are 0.51, 0.65, and 0.65 to attain sufficient workability values. Properties like the particle shape of clay minerals, which cause an excessively high water demand due to the penetration of water into the interlayers of the clay, do not affect the workability [197,198].

6.2. Water absorption and sorptivity

The concrete durability around an exposed surface is mainly determined by the ability of harmful agents to penetrate the concrete. The sorptivity depends on the porosity and permeability of the concrete and the strength of the capillary [199]. It is essential to reduce the penetration of harmful agents' sorptivity of the geopolymer. Portland cement paste exhibits higher porosity and water absorption capacity than geopolymer pastes [200]. Most of the time, steam-curing affects things like the uniform distribution of hydration products and the porosity of Portland cement paste [201].

Aydın and Kızıltepe [201] reported that the sorptivity and water absorption capacity of activated waste clay containing boron mortars declined with an increase in SiO_2/Na_2O values, and Na_2O-containing mortar mixtures exhibited smaller water absorption values and sorptivity than the control mortar. The Ms and Na_2O content of the activating solution greatly affect the water sorptivity more than the total absorption capacity, which conforms with the report of Bernal, de Gutiérrez, Pedraza, Provis, Rodriguez and Delvasto [202].

Falah, Obenaus-Emler, Kinnunen and Illikainen [203] reported that water absorption can be suppressed by maximizing the sodium silicate content, thereby enhancing the compressive strength. Of all the samples, submicron alkali-activated mine tailings with a sodium silicate composition of 30 wt% and cured for 28 days exhibit the lowest water absorption, resulting in maximum compressive strength of about 27.31 MPa due to the higher reaction rate. According to the authors, water absorption increased from 10% to 17% due to increased pore structure influenced by the curing conditions. Moreover, the water absorption capacity of the samples decreased with an increasing concentration of Na_2SiO_3, indicating lower porosity (a denser structure) [204]. The reduction in the water absorption caused by the increasing concentration of Na_2SiO_3 slightly enhanced the compressive strength. The minimum water absorption of the samples cured for 28 days at 40 °C and 60 °C is obtained from alkali-activated mine tailings treated with 30 wt% The Na_2SiO_3 content is 12.62 and 9.98%, indicating a higher degree of a reaction than other samples and giving the highest compressive strength of 15.84 and 22 MPa. Moreover, the report of Falah, Ohenoja, Obenaus-Emler, Kinnunen and Illikainen [205] shows that water absorption increased from 10 to 14% when the submicron size of the mine tailings was used. The amount of submicron mine tailings and Na_2SiO_3 in the sample led to a decrease in the sample's ability to absorb water. This is because the sample has a dense structure that does not allow water to pass through [206].

Regardless of tailings source or mineralogy/composition, grinding time is a major parameter influencing the water absorption capacity [207]. It has been reported that the adsorption capacity of alkali-activated silicate tailings declines significantly with increasing tailing time. The alkali-activated silicate rich in epidote with high aluminum and the silicate rich in tremolite with high magnesium, exhibited about 20% and 35% water absorption, respectively, after grinding for 1 min. However, when the grinding time was increased to 16 min, the adsorption capacity of the two samples dropped by about two times. This is because the microstructure of the alkali-activated tailings changed a lot when the time was increased.

7. Mechanical properties of mine tailings geopolymers

7.1. Mine tailings as aggregates for geopolymer

Mine tailings, a waste comprising finely distributed silica, might be regarded as aggregates of geopolymer and alkali-activated materials because of their high silica content. Mine tailings recycling, in conjunction with the diminution of the ecological burden from mine waste, is intended to lower the cost of geopolymer concrete while also protecting natural mineral sources.

Barrie, Cappuyns, Vassilieva, Adriaens, Hollanders, Garcés, Paredes, Pontikes, Elsen and Machiels [208] utilized gold mining tailings as fine aggregates to substitute cement sand in a geopolymer based on volcanic and halloysite glass. It has been established that the incorporation of 12.7% mine tailings into the geopolymer has no impact on the mechanical characteristics of the material. When the geopolymerization process was done, the resultant specimens had good immobilization of Zn and Pb, but Cu was more mobile because of the high pH level in the. water.

A geopolymer mortar comprised of metakaolin and quartz was created by substituting iron mine tailings for natural quartz material. As demonstrated in the previous experiment, the introduction of mine tailings had no considerable influence on the mechanical properties of the geopolymers. In contrast to the reference specimens (with quartz aggregate), the specimens comprising mine tailings were recognized by increased porosity and water absorption. This might have a detrimental impact on the material's durability. A similar investigation was conducted by Sharath, Shivaprasad, Athikkal and Das [153], who utilized gold mining tailings as fine aggregates to substitute cement sand in a geopolymer based on volcanic and halloysite glass. It has been established that the incorporation of 12.7% mine tailings into the geopolymer has no impact on the mechanical characteristics of the material. When the geopolymerization process was done, the resultant specimens had good immobilization of Zn and Pb, but Cu was more mobile because of the high pH level in the water. Paiva, Yliniemi, Illikainen, Rocha and Ferreira [155] employed high-sulfidic mine tailings as a fine aggregate of metakaolin-based geopolymer composite (metakaolin-geopolymer) or blast furnace slag-based geopolymer composite (BFS-geopolymer) to create a fine aggregate of geopolymers. A stronger compressive strength (>20 MPa) and a more rapid reactive nature were observed in metakaolin-based geopolymers compared to BFS-based geopolymers. Furthermore, when evaluated under extremely harsh circumstances (pH 4 and 7 for 40 days), the compositions comprising a high concentration of mine tailings (50–62 wt% of precursor) displayed substantial chemical resistance. Table 4 presents a summary of the impacts of employing tailings as aggregates in geopolymer mixes.

7.2. Mine tailings as precursors for geopolymer

A range of chemical properties identifies the minerals that make up the composition of mine tailings, including their interaction with alkalis. The aluminosilicate framework of the geopolymer is defined by the interaction of the precursor's mineral constituents in an alkali-activated solution, as well as the structure and properties of the geopolymer itself. In general, the alkaline interaction of mine tailings is low, and this is the most substantial factor to consider when incorporating mine tailings into geopolymers.

Mine tailings have a high silica content as shown in Table 2, which raises the molar proportion SiO_2/Al_2O_3 in mine tailings-geopolymer composites, which has a detrimental impact on the geopolymerization process. For this reason, metakaolin is the most frequently utilized as a supplementary source of Al in the chemical industry [65,97,210–215] because of the uniformity and purity of its composition, as well as its high interaction [97]. Falayi [160] has indicated that fly ash and blast furnace slag (BFS) are employed a bit less frequently than other substances. It has been reported that volcanic glass and waste glass have been utilized, as well as aluminum oxide and aluminum sludge, calcined halloysite, and low-calcium slag [94,189]. Fig. 6 shows a source of

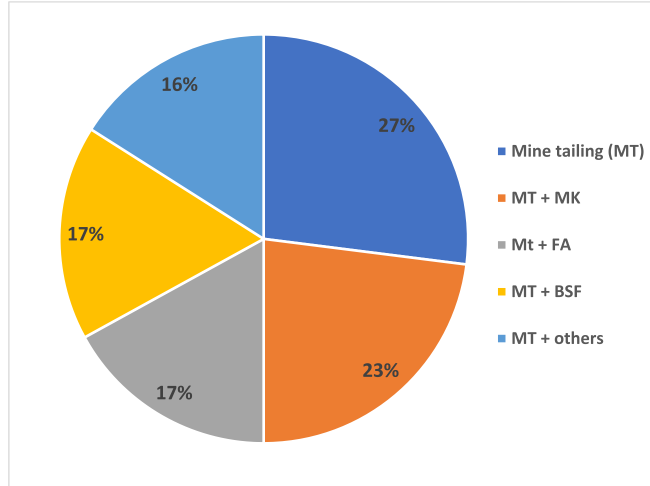


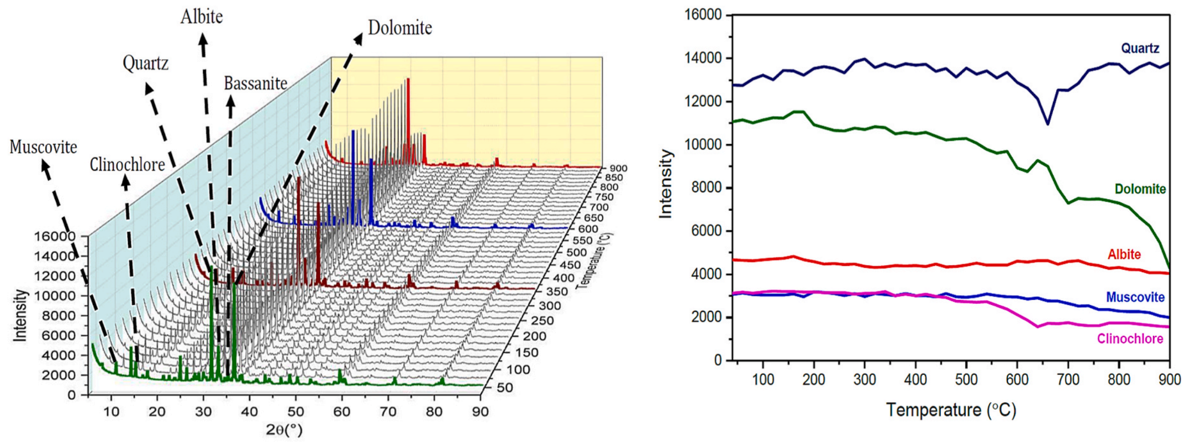
Fig. 6. Source of geopolymer precursors utilized with mine tailings for the production of mine tailings-geopolymer composites [59].

geopolymer precursors that can be used with mine tailings to make mine tailings-geopolymer composites.

The strength and deformation characteristics of mine tailings-geopolymer composites are influenced by a variety of parameters, including the Si/Al proportion, particle size, type of alkali-activated, alkali-activated/binder ratio, and curing technique. It is critical to note that the enhanced interaction of mine tailings in geopolymerization has an effect on the mechanical properties of geopolymers, which is a useful consideration in the usage of mine tailings in geopolymerization. Because of the poor interaction of mine tailings, extra pre-treatment processes are required. Pre-treatment of mine tailings has also been found to have a beneficial influence on its interaction and eventual geopolymer due to the microstructural and mineralogical changes that occur during these processes. Mechanical activation is frequently accomplished in mills, such as planetary mills, roller mills, ball mills, jet mills, and agitation mills, among other types of equipment [184, 216–222]. Furthermore, mechanical activation has the potential to significantly affect both the chemical and physical properties of mine tailings; these effects boost the concentration of aluminosilicate in alkaline solution, which favors the geopolymerization reaction. In some circumstances, thermal pre-treatment might be used instead of mechanical activation. Its formation is induced by heating raw material to a certain temperature and creating structural changes, the effects of which

Table 4
Summary of the impacts of employing tailings as aggregates in geopolymer mixes.

mine tailing Types	geopolymer precursors	mine tailings in geopolymer blends	mine tailings replacement (wt%) of precursor	mine tailings Impacts	Refs
Copper, zinc	BFS-geopolymer composites & metakaolin -geopolymer composites	As admixture	50–65	Enhancing chemical resistance; altering the rheological characteristics	[155]
Iron	fly ash-geopolymer composites	As admixture	10–35	Improved setting time and workability; increased compressive strength and heat resistance; dropped porosity and microcracking's	[174]
	fly ash-geopolymer composites	As fine aggregates	33.5	Lesesne the time required for setting; improve the compressive strength and density	[153]
	metakaolin -geopolymer composites	As fine aggregates	50 or 100	There is no impact on the mechanical characteristics; nevertheless, the porosity and water absorption are increased	[209]
Gold	Volcanic glass-geopolymer composites & calcined Halloysite-geopolymer composites	As fine aggregates	12.50	There is no detrimental impact on the mechanical characteristics	[208]
Quartz	metakaolin -geopolymer composites	As admixture	10–32	Increase in viscosity; lowering in flowability and shrinkage during drying; no adverse impact on mechanical characteristics	[169]



(a) (b)

Fig. 7. (a) XRD analysis of mine tailings through heat treatment; (b) Intensity variance for some main components [161].

rely on a range of elements such as the heating rate, holding temperature and duration, the environment, and the rate at which the raw material is heated [223]. Mineral changes occur as a consequence of the thermal pre-treatment; in some cases, the elevated temperature might surpass the breakdown temperature of the minerals being treated. The removal of diaspore and kaolinite was observed by Ye, Zhang and Shi [133] after calcining bauxite tailings at 800 °C for 1 h, which increased the interaction of the mine tailings during geopolymerization. As shown in Fig. 7, after thermal treatment at almost 600 °C, Kiventerä, Sreenivasan, Cheeseman, Kinnunen and Illikainen [161] noted a decrease in the dolomite peak shown by gold tailings. When heated over 400 °C, basanite transforms into anhydride. On the other hand, the quartz amount remained stable until 650 °C, when it declined slightly.

As indicated in Tables 5 and 6, there are a number of factors that influence the mechanical properties, compressive strength, and flexural strength of various kinds of mine tailings used as a geopolymer source. They are commonly coupled with other alumina-silicate source materials, such as fly ash, BFS, metakaolin, and so on, for the production of geopolymers. According to these tables, the compressive and flexural strengths of all mine tailings-geopolymer composites were quite different. This was mostly because they used several types of mine tailings, several types of alumina-silicate resources, several types of alkali-activated, different alkali-activated/binder proportions, different temperatures, and different humidity levels when they made them.

The curing temperature of mine tailings-geopolymer composites has a substantial impact on the mechanical and microstructural characteristics of the polymers. Tian, Xu, Song, Rao and Xia [173] studied the impact of curing temperature on the characteristics of copper tailing-based geopolymers. When the curing temperature was somewhat enhanced (22–80 °C), homogeneous dissolution of aluminosilicate and the development of N–A–S–H and C–S–H gels were encouraged, resulting in a beneficial impact on compressive strength. A rise in the curing temperature over 80 °C, on the other hand, had the opposite impact. The high curing temperatures (between 100 and 125 °C) resulted in a lowering of the amount of alkaline medium present, which prevented the dissolution of silica and alumina types.

Several researchers evaluated the compressive and flexural strengths of geopolymers made using copper mine tailings as raw material and activated with a range of alkali activated. In its investigation, Falah, Obenaus-Emler, Kinnunen and Illikainen [224] discovered that increasing the amount of sodium silicate used, as well as the curing period and curing temperature, enhanced the compressive strength of copper mine tailings-geopolymer composites. The copper mine tailings-geopolymer composites, which had been activated by sodium silicate solution, were baked in a moderate-temperature oven. They also observed that the flexural strength of copper mine tailings-geopolymer composites improved in a way similar to that shown in the compressive strength relates. Similarly, in the works of Ahmari and Zhang [86], Manjarrez, Nikvar-Hassani, Shadnia and Zhang [158] an increase in compressive strength has been seen with an increase in the molarity of sodium hydroxide in the related copper mine tailings-geopolymer composites activated by sodium hydroxide.

The compressive strength of a copper mine tailings-geopolymer composite activated by sodium hydroxide improved with a boost in forming pressure throughout moulding in the investigation of Ahmari and Zhang [225], but only up to a water content of 12% at the outset, and then the compressive strength dropped with a rise in forming pressure as shown in Fig. 8 once the water content was exceeded. They also discovered that after being submerged in water, compressive strength dropped considerably. Additionally, Manjarrez and Zhang [172] demonstrated that a lowering in moisture content below 14% resulted in an improvement in the compressive strength of copper mine tailings-geopolymer composites triggered by sodium hydroxide. The rise in curing temperature up to 90 °C also resulted in an improvement in the compressive strength of a copper mine tailings-geopolymer composite activated by sulfur dioxide [225].

When further alumina-silicate source materials are added, the compressive strength of copper mine tailings-geopolymer composites improves [158]. In addition, a rise in copper slag concentrations, a rise in sodium silicate/sodium hydroxide proportions up to 1.0, and a rise in the molarity of sodium hydroxide solutions up to ten molarity all led to an improvement in the compressive strength of copper mine tailings-copper slag blended geopolymer [226,227].

Iron mine tailings-geopolymer composites are produced in a way similar to copper mine tailings-geopolymer composites, with or without the incorporation of alumina-silicate source components. In one investigation, the compressive strength of an iron mine tailings-geopolymer composite activated by sodium silicate was improved with a rise in curing temperature up to 80 °C and a rise in curing period up to 7 days, after which the compressive strength declined [148].

The geopolymer constructed from gold mine tailings and different alkali-activated, as well as additional alumina-silicate components, has been the topic of a few studies to which researchers have given special attention. Gold mine waste-geopolymer composites were created by Falayi [228] utilizing potassium aluminate, potassium silicate, and potassium hydroxide activators. According to its findings, the maximum compressive strength of gold mine tailings-geopolymer composites was discovered at a potassium silicate/potassium hydroxide proportion of 1.1. According to its findings, raising the curing temperature from 65 to 100 °C enhanced the compressive strength of potassium aluminate and potassium hydroxide-activated gold mine tailings-geopolymer composites. The researchers also discovered that the compressive strength of

Table 5
Compressive strength for various mine tailings-geopolymer composites.

Mine tailing types	geopolymer precursors	Content of precursors, (wt%)	Alkaline activators	Curing Tem (∘C)	Compressive Strength (MPa) (Age, d)	Refs
Bauxite	Slag	30	SS & SH	20	34 (3 d)	[133]
		30	SS & SH	20	52 (28 d)	
		30	SS & SH	20	68 (912 d)	
		30	SS & SH	20	74 (1460 d)	
		30	SS & SH	20	75 (2190 d)	
	BFS	30	SS & SH	1-20	8–25 (1 d)	[232]
		30	SS & SH	1-20	17–45 (3 d)	
		30	SS & SH	1-20	23–58 (28 d)	
		30	SS & SH	1-20	42–72 (60 d)	
		30	SS & SH	1-20	62–76 (90 d)	
Copper	Low-Ca slag	0-50	SS & SH	45-75	13–23.5 (7 d)	[158]
	-	-	SH	35	0.3–5.3 (7 d)	[172]
	Aluminum sludge	0-20	SH	95	11–45 (7 d)	[189]
	Low-Ca flash-furnace copper smelter slag	0-100	SH	65-105	1–76 (7 d)	[235]
	-	-	n.m.	n.m.	3–33.6 (7 d)	[227, 234]
	fly ash	0-100	SH	60	3–7 (2 d)	[236]
		0-100	SH	60	4–8.9 (7 d)	
		0-100	SH	60	4–8.1 (14 d)	
		0-100	SH	60	4–8.5 (28 d)	
Copper/zinc	metakaolin	50, 62	SS & SH	20-50	14–32 (28 d)	[155]
	BFS	0, 50, 62	SS & SH	20-50	14–15.4 (28 d)	
Garnet	metakaolin	0-100	SS & SH	20-50	1–45 (3 d)	[167]
Gold	fly ash	0-50	-	-	1–12 (3 d)	[228]
	Basic oxygen furnace slag	0-50	-	-	1–22 (3 d)	
	BFS	10, 25	SS, SH & CH	Ambient	6–19 (28 d)	[155, 237]
Iron	-	-	SH	100	18–112.8 (7 d)	[139]
	Glass wool residue	10-30	SH	100	19–41.9 (7 d)	
	fly ash	70, 80, 90, 100	n.m.	n.m.	42–49 (28 d)	[141, 238]
	-	-	SS	80	1–34 (3 d)	[12]
		-	SS	80	50.5 (7 d)	
Kaolinite	-	-	-	40 & Ambient	12–15 (7 d)	[166]
Phosphate	metakaolin	30, 40	SS & SH	60 & Ambient	24–39.94 (28 d)	[97]
	-	-			4 (7 d)	[3]
		-	-	40 & Ambient	4–7 (7 d)	[166]
	metakaolin	50, 100	SS & SH	60, 85 & Ambient	12.8–53 (14 d)	[83,97]
	fly ash	50, 100	SS & SH	60, 85 & Ambient	13.3–62 (14 d)	
Quartz	metakaolin	700, 80, 90	KH & KS	20	12.8–15 (1 d)	[169]
		70, 80, 90	KH & KS	20	16–18.5 (7 d)	
		70, 80, 90	KH & KS	20	17–20 (28 d)	
Sphalerite	metakaolin	0, 10, 20,30, 40, 50	SS	60 & Ambient	2–15 (7 d)	[170]
Tungsten	WG	0, 20, 30, 40	SS & SH	20-80 & 20	0.6–29 (1 d)	[239]
		0, 20, 30, 40	SS & SH	20-80 & 20	0.6–32 (3 d)	
		0, 20, 30, 40	SS & SH	20-80 & 20	0.6–34.5 (7 d)	
		0, 20, 30, 40	SS & SH	20-80 & 20	2.6–39.6 (28 d)	
Vanadium	metakaolin	30	SH	Ambient	2.6–29 (7 d)	[164]
		N.M.	SS	Ambient	8.6–22.5 (7 d)	[150]
		N.M.	SS	Ambient	8.6–25 (14 d)	
		0, 10, 20, 30, 40	SH	20 & Ambient	10.8–55.6 (7 d)	[240]
Zinc	metakaolin	0, 10, 20, 30, 40, 50	SS	60 & Ambient	1.2–30.2 (7 d)	[183]

Where:Blast furnace slag (BFS); Fly ash (fly ash); Metakaolin (metakaolin); Waste glass (WG); not mention (n.m); sodium silicate (SS); sodium hydroxide (SH); calcium hydroxide (CH); potassium silicate (KS); potassium hydroxide (KH).

geopolymer activated by potassium aluminate and potassium hydroxide activators is greater than that of geopolymer activated by potassium silicate and potassium hydroxide activators, even when the curing temperature is raised to up to 100 °C.

According to an investigation conducted by Pardavé, Epalza, Durán and Lóvera [229], when the curing duration was increased, there was an increase in the compressive strength of gold mine tailings and alumina/kaolin mixed geopolymer. In addition, the investigation by Kiventerä, Yliniemi, Golek, Deja, Ferreira and Illikainen [230] found that rising the slag concentrations and molarities of sodium hydroxide solutions resulted in an improvement in the compressive strength of gold mine tailings-slag/metakaolin blended geopolymer as shown in Fig. 9 [230].

Solismaa, Ismailov, Karhu, Sreenivasan, Lehtonen, Kinnunen, Illikainen and Räisänen [231] discovered that incorporating 25% metakaolin improved the compressive strength of mine tailings-geopolymer composites made with a sodium hydroxide activator. They also found a significant difference in compressive strength when the curing temperature went up to 65 °C. At 85 °C, the compressive strength went down a lot. Concerning the compressive and flexural strengths of geopolymer, no set optimal quartz mine tailings quantity has been seen for any of the curing times tested. Quartz mine tailings that contain 30% or more quartz shrink when they dry, but geopolymer shrinks less and has less porosity when the quartz content is more than 30%. In contrast to other

Table 6
Flexure strength for several mine tailings-geopolymer composites.

Mine tailings type	geopolymer precursors	Content of precursors, (wt%)	Alkaline activators	Curing Tem (oC)	Flexure strength (MPa), (Age-Days)	Refs
Bauxite	Slag	30	SS & SH	20	5.3 (3 d)	[133]
		30	SS & SH	20	8 (28 d)	
		30	SS & SH	20	9.85 (912 d)	
		30	SS & SH	20	10 (1460 d)	
		30	SS & SH	20	10.3 (2190 d)	
	BFS	30	SS & SH	1-20	3.3–4.7 (1 d)	[232]
		30	SS & SH	1-20	4.0–6.6 (3 d)	
		30	SS & SH	1-20	5.5–7.6 (28 d)	
		30	SS & SH	1-20	6.2–10.9 (60 d)	
		30	SS & SH	1-20	6.8–10.4 (90 d)	
Iron	-	-	SH	100	4.9–21.4 (7 d)	[139]
	Glass wool residue	10-30	SH	100	2.05–4.7 (7 d)	
Quartz	metakaolin	70, 80, 90	KH & KS	20	1.7–2.1 (1 d)	[169]
		70, 80, 90	KH & KS	20	2.0–2.5 (7 d)	
		70, 80, 90	KH & KS	20	2.0–2.5 (28 d)	

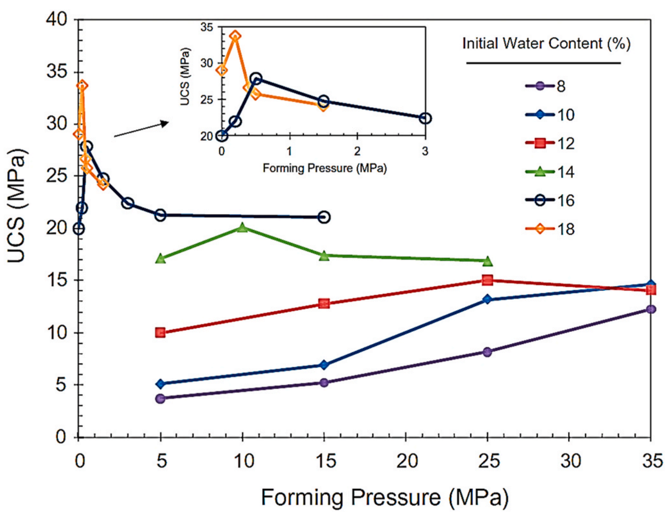


Fig. 8. Unconfined compressive strength (UCS) versus forming pressure for samples produced at varying water contents, including 15 molarity NaOH dosage and cured at 90 °C for 7 days [234].

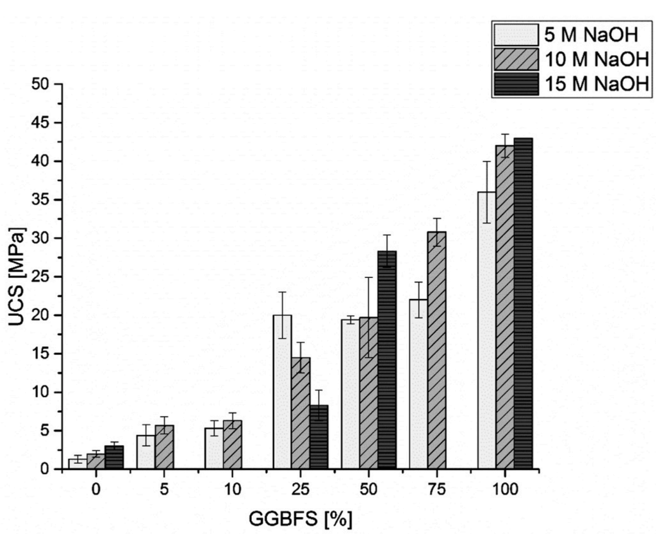


Fig. 9. Unconfined compressive strength (UCS) of bricks with varying GGBFS- and NaOH– content after 28 days [230].

mine tailings-geopolymer composites, the compressive strength of zinc tailings and metakaolin-geopolymer composites improves with a rise in the amount of mine tailings present [170,183]. Wei, Zhang and Bao [150], Jiao, Zhang and Chen [165], both published investigations on vanadium mine tailings-geopolymer including fly ash and metakaolin, respectively, as additional raw materials of alumina-silicate in addition to vanadium mine tailings.

Ye, Zhang and Shi [232] observed an advancement in compressive strength and flexural strength with an addition in time at low-curing temperature in an unknown mine tailings-geopolymer composite containing % slag in an unreported mine tailings-geopolymer composite. This demonstrates that the compressive and flexural strengths of concrete cured at low temperatures are less than those of concrete cured at a typical temperature of 22 °C. One possibility for the poor compressive and flexural strengths of such geopolymers might be the sluggish geopolymer reaction occurring at such low temperatures.

It is feasible to enhance the mechanical properties of mine tailings-geopolymer composites by introducing reinforcing fibers. By studying a specimen of geopolymer matrix produced from non-heated phosphate mine tailings, Haddaji, Majdoubi, Mansouri, Tamraoui, Manoun, Oumam and Hannache [233] demonstrated that the incorporation of synthetic fibers (glass and polypropylene) promotes more energy absorption and ductile failure as a result of the stress redistribution and the fiber's bridging impact. The 1% synthetic fibers produced the best mechanical qualities, according to the research. When flexural strength was improved relative to the original mine tailings-geopolymer composite matrix, the percentage increase was 277% for polypropylene fibers and 27% for glass fibers, respectively.

8. Durability properties

Only a few researchers have examined the long-term durability of mine tailings-geopolymer composites. With the help of Caballero, Sánchez and Ríos [241], the gold mine tailings-geopolymer was exposed to sulfate and acid solutions as well as high temperatures. According to its findings, as compared to a reference cementitious composite, the rate of loss in compressive strength with immersion time in sulfuric and nitric acid solutions is pretty equal in gold mine tailings-geopolymer composites. Similar results have been seen in magnesium and sodium sulfate solutions, as well as when the solutions are exposed to high temperatures. Ahmari and Zhang [225] discovered that copper mine tailings-geopolymer composites submerged for 120 days in aqueous solutions with pH values ranging between 4 and 7 had a substantial drop (by 58–79% compared to reference specimens) in their plain compressive strength. The high initial Si/Al proportion and partial geopolymerization of the mine tailings, according to the scientists, were responsible for this result. Water absorption and weight loss, on the other hand, were quite minor and had lower values in comparison to the

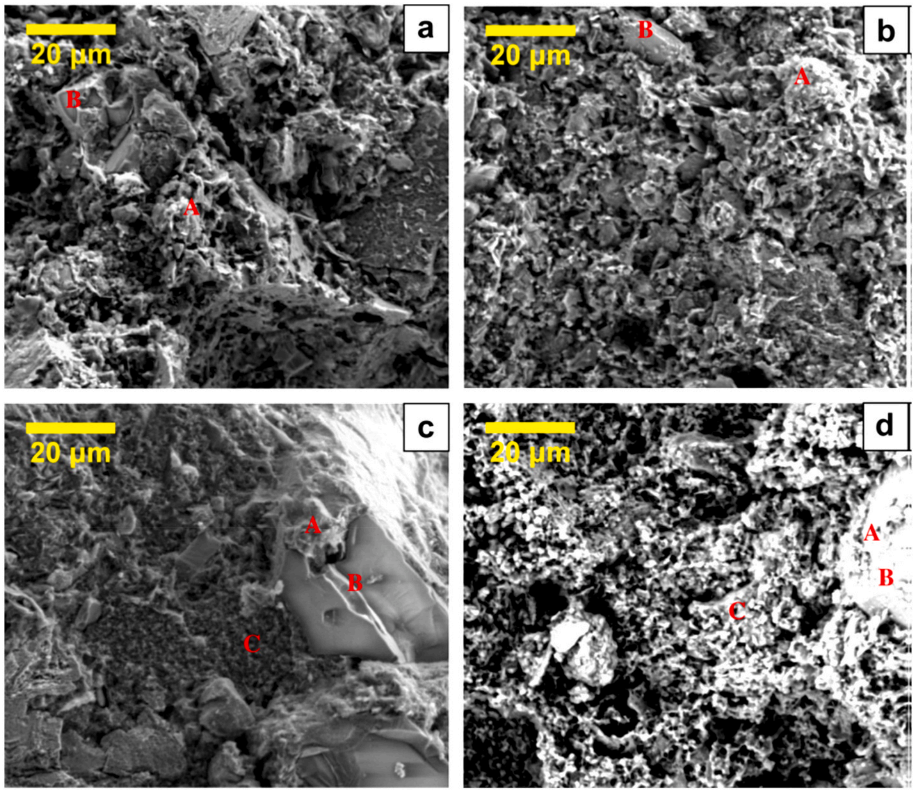


Fig. 10. SEM image of geopolymer brick samples made at 15 molarity NaOH, 16% water content, and cured for 7 days at 90 °C: (a) 0% cement kiln dust, (b) 5% cement kiln dust, (c) 10% cement kiln dust, and (d) 10% cement kiln dust and after immersion in water for 7 days. (a and c indicate the binder stage, while b indicates the unreacted stage) [86].

OPC-based binding agent. Another study by Ahmari and Zhang [86] showed that introducing cement kiln dust can improve durability and unconfined compressive strength. The beneficial impact of cement kiln dust was connected to improved aluminosilicate dissolving, production of calcium carbonate, and calcium incorporation into the geopolymer system. Falayi [228] demonstrated that activating with potassium aluminate results in a better resistance of geopolymers to alternate wetting and drying than potassium silicate. In every case, the UCS values dropped more than threefold after 10 wet and dry cycles. This makes it difficult to use these composites in places where there is a lot of wet and dry time, and it also makes it important to look into ways to mitigate this.

The utilization of tailings to substitute natural aggregates (gravel or sand) in geopolymer concretes, either partially or completely, might lead to an upsurge in the water absorption and porosity of the latter [209]. In turn, this can make these substances more vulnerable to chemical assault, which can have a detrimental impact on their overall durability. Further investigation in this field is needed because of a lack of understanding about these and other characteristics of the durability of mine tailings-geopolymer composites, which suggests a need for future research in this area.

9. Microstructure properties

The microstructure of geopolymerization products; the content, structure, and proportion of the produced amorphous and crystalline phases; as well as the existence, distribution, and size of pores, are all useful factors in determining the attributes of mine tailings-geopolymer composites.

Falah, Obenaus-Emler, Kinnunen and Illikainen [224] found that rising the sodium silicate content of a copper mine tailings-geopolymer composite by up to 30% densifies the microstructure of the material. It was also discovered that, at such a concentration of sodium silicate, almost the whole geopolymer is changed into fused rectangular prisms, which indicates a full transition to high alkaline conditions. Manjarrez, Nikvar-Hassani, Shadnia and Zhang [158] have discovered that when copper slag is put into its geopolymer, the density of the geopolymer rises as assessed by SEM image analysis. Its results show that copper slag increased the breadth of the amorphous peak in the XRD of copper mine tailings-geopolymer composites, whereas the crystalline peak in the copper mine tailings remained the same after geopolymerization, which is compatible with the SEM findings.

The XRD examination findings of its 28-day-cured geopolymer also reveal a lowering in the ferocity of crystalline peaks, suggesting that the dissolution of the Al and Si components in the geopolymerization process has progressed farther than previously thought. SEM pictures of copper mine tailings-geopolymer composites obtained in the work by Ren, Zhang, Ramey, Waterman and Ormsby [189] show that raised aluminum sludge levels lead to the development of more geopolymer gels. In addition, they verified that there were no unreacted particles at an aluminum sludge concentration of 21% in their experiment. According to Ahmari and Zhang [86] investigation, as shown in Fig. 10, the enhanced microstructure of copper mine tailings-geopolymer composites is due to the incorporation of cement kiln dust, which leads to the creation of more geopolymer gels, as seen by an increased Si/Al ratio.

Due to the incorporation of iron mine tailings into fly ash-geopolymer composites, Duan et al. demonstrated that the geopolymer became denser by producing more C–S–H [136,141]. They also analyzed the microstructure of their geopolymer after it had been subjected to elevated temperatures and discovered that it had suffered no considerable damage to its microstructure after seven heating cycles at 200 °C. Increased numbers of pores and fractures were found after 800 °C exposure in fly ash-geopolymer composites that did not include iron mine tailings, but this was not the case in fly ash-geopolymer composites that included iron mine tailings after the same exposure.

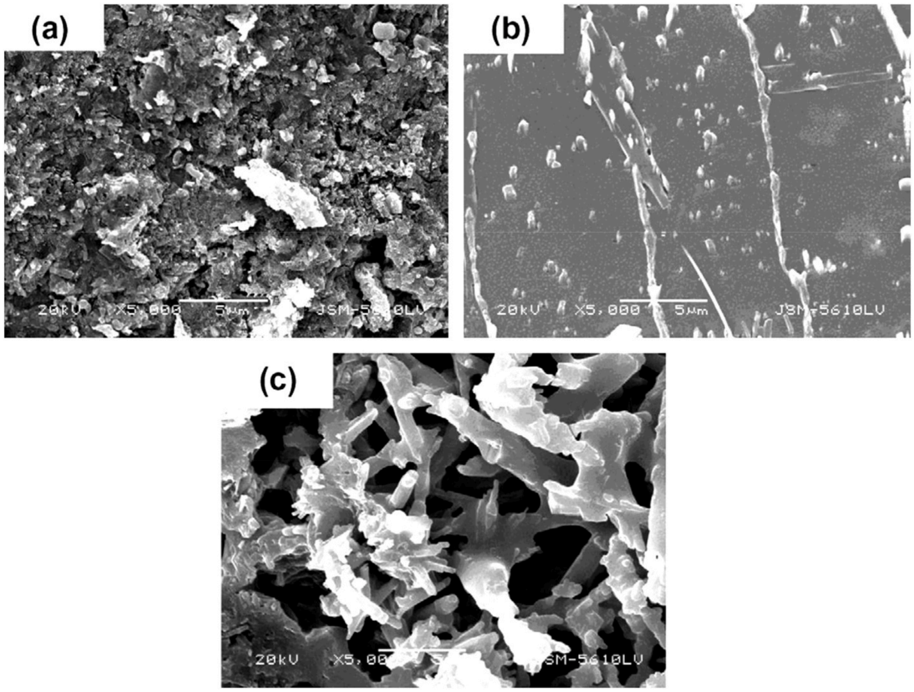


Fig. 11. SEM microanalysis of the geopolymer specimen: (a) ambient temperature; (b) at 900 °C; and (c) at 1050 °C [165].

10. Thermal properties

As previously stated, geopolymers, in contrast to OPC binders, are recognized for their high thermal stability and the ability to retain strength even after being subjected to high temperatures [242,243]. This is because of the unique characteristics of its structure, which is formed by branched AlO_4 and SiO_4 tetrahedral frameworks [242,243]. The type of aggregate used to make geopolymers also plays a key role in the advancement of their thermal properties. This is because geopolymers can be made with several types of aggregates, such as aluminum-silicate aggregates. It should be noted that, when geopolymers have tails, a careful study of how these materials change and how well they work like insulation and fire-resistant materials is needed to figure out if they can be used.

Ye, Zhang and Shi [134] investigated the impact of raised temperatures on the characteristics of a geopolymer made from bauxite tailings and slag. They discovered that the compressive strength of geopolymer is somewhat boosted after exposure to 200 °C but that it rapidly reduces after exposure to 600 °C. However, the drop in compressive strength was substantial between 600 and 1000 °C, with a little gain in compressive strength at 1200 °C. Anorthite ($CaAl_2(SiO_4)_2$), a type of ceramic, was discovered to be associated with an increase in strength, which could be attributed to self-healing and densification caused by sintering. The noticed drop in compressive strength at temperatures reaching 800 °C is because of the dissolution of the amorphous stage as well as an extra thermal mismatch between the contracting gels throughout the contracting process. There is also physical harm in the form of cracking on the surface of samples. This is also in line with the findings of the compression experiment, which showed that there is no severe cracking on the sample when it reaches 400 °C. It gets more violent as the temperature rises, so it starts at 600 °C and goes up to 1200 °C. Also, the width of micro-pores in its geopolymer gets bigger as the temperature of the material gets higher.

According to Jiao, Zhang and Chen [165], the strength gain of mine tailings-geopolymer composites when subjected to high temperatures has also been reported. As a result of sintering, the geopolymers produced by the alkali-activated of vanadium tailings with high silica content demonstrated an improvement in compressive strength at temperatures above 900 °C. This was accompanied by a lowering in the content of unreacted aluminosilicate precursor particles and the development of a denser microstructure by means of sintering, as shown in Fig. 11. As illustrated in Fig. 12, heating to 1000 °C reduces bulk density and strength while increasing fracture and porosity. This effect was revealed to be caused by volume expansion and severe thermal incompatibility.

11. Leaching behavior

Heavy metals are naturally occurring elements that comprise essential (e.g., Cu, Fe, Ni, and Zn) and nonessential metals (Cd, Hg, and Pb) [244]. These metals are released into the environment by both natural and anthropogenic sources such as industrial discharge, automobiles exhaust, and mining. For example, toxic heavy metal ions, as one of the most common pollutants in wastewater, are harmful and widespread, which have severely threatened human health and survival. Therefore, the removal of toxic heavy metal ions from wastewater is becoming an intractable problem. In recent years, geopolymer-based zeolite functional materials have been considered as promising

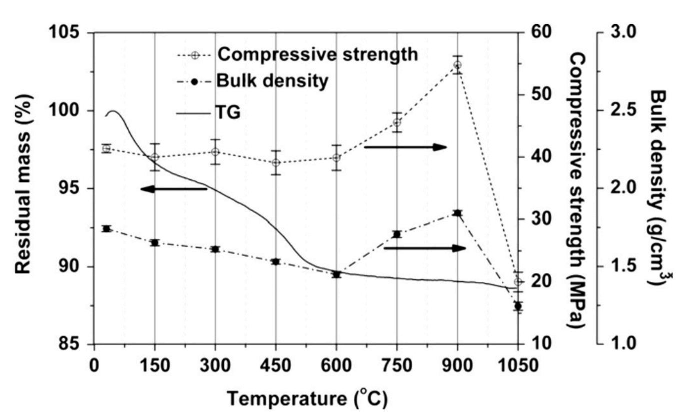


Fig. 12. Compressive strength, residual mass, and bulk density of the geopolymer specimen at high temperatures [165].

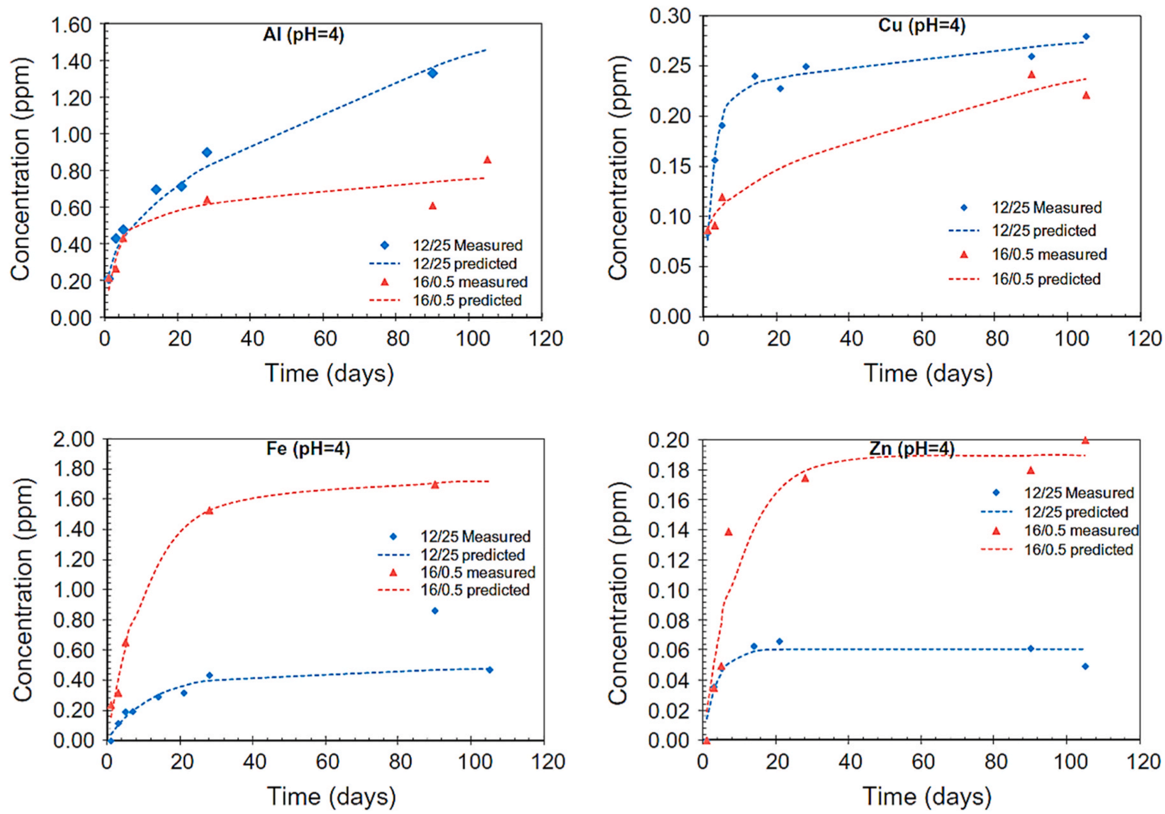


Fig. 13. Measured and predicted concentrations of heavy metals at pH = 4 a by first-order reaction/diffusion model (FRDM) [225].

adsorbents for the efficient removal of toxic heavy metal ions from wastewater due to their wide range of solid raw materials, low price, and efficient adsorption properties [245].

The presence of various heavy metals in mine tailings is a major environmental concern. To prevent their spread in soils and groundwater due to leaching, solidification (stabilization) through geopolymerization can be considered as one of the sustainable methods for neutralizing tailings containing toxic elements. In this regard, leaching characteristics are important indicators describing the effectiveness of heavy metal immobilization in geopolymers. As a result, making mine tailings-based geopolymers requires extra care when choosing the best ways and parts to make them.

The ability to successfully immobilize the heavy metals contained in lead-zinc tailings via physical and chemical ways was demonstrated by Zhao, Xia, Yu, Huang, Jiao and Li [67] in geopolymer based on coal gangue and blast furnace slag. Although an increase in tailings in prepared samples led to an increase in the concentration of Zn^{2+}, Pb^{2+}, and Cd^{2+} in the leaching solution, these values remained within acceptable limits [67]. The obtained geopolymer samples were characterized by a compact structure, wherein the crystalline phase Zn^{2+} was found; the amorphous phases were characterized by the content of Pb^{2+} and Cd^{2+}.

Heavy metal cations can form chemical bonds with reactive components during polycondensation, which can lead to the formation of new phases. The formation of the PbO/BaSiO3 phase was observed by Hu, Zhong, Yang, Bai, Ren, Zhao, Zhang, Ju, Wen and Mao [246] in rare earth tailing-based geopolymers. This is because $Pb2^{+}$ and $Ba2^{+}$ interact with unbridged oxygen or the Si/Al chain, which makes sure that the heavy metals stay in place inside the framework.

Ahmari and Zhang [86] reported no effective immobilization of arsenic and molybdenum due to geopolymerization in copper mine tailings-based geopolymers [225]. The authors also suggested a methodology to predict trace elements in geopolymers (Fig. 13). The experimental leaching data in their investigation correlates well with the proposed paradigm. Many studies have examined the efficiency of gold mine tailings-based geopolymers in immobilizing heavy metals [228, 230]. It is observed that the immobilization efficiency of Cr, Cu, Zn, Ni, and Mn in gold mine tailings, metakaolin, and slag blended geopolymer is higher than 98% with the only exception of arsenic and vanadium (Va), whose leaching is higher in that geopolymer [230].

In gold mine tailings-based geopolymers, the immobilization efficiency of heavy metals is higher in PA and KOH activated gold mine tailings geopolymers than in those synthesized by PS and KOH [228]. Kiventerä, Sreenivasan, Cheeseman, Kinnunen and Illikainen [161], Kiventerä, Lancellotti, Catauro, Dal Poggetto, Leonelli and Illikainen [237] also reported effective immobilization of sulfate and arsenic in gold mine tailings-based geopolymer using calcium hydroxide and slag. After 7 days of curing, their geopolymer contains over 90% sulfate and over 95% arsenic, with other heavy elements immobilized as well. Wan, Rao, Song, Leon-Patino, Ma and Yin [170], Wan, Rao, Song and Zhang [183]reported that lead (Pb) can be effectively immobilized in the mine tailings-geopolymer. They found that the formation of geopolymer gel in the binders is very important to the immobilization of Pb.

12. Applications

Utilizing mine tailings as a commodity to make geopolymer is a promising idea for making it more widely utilized. A lot of articles have looked into how mine tailings-geopolymer composites could be utilized. Mine geopolymers are a suitable candidate for recycling mine waste, construction, stabilizing chemicals, and backfilling mine putty to keep harmful elements out. This strategy not only reduces OPC's carbon footprint but also prevents environmental damage caused by the piling of mining debris. Table 7 shows the many ways mine tailings can be utilized as source substances or aggregates for geopolymer materials based on previous work.

Table 7
Various applications of mine tailings-geopolymer composites.

Mine tailing types	geopolymer blend types	Remarks	Applications	Refs.
Copper	fly ash-geopolymer composites	Microstructures that are the same across the board	Binder materials	[173]
	cement kiln dust-geopolymer composites	high compressive strength; high durability	Bricks	[86, 225]
	-	Stability in chemical terms		[159]
	-	High compressive strength		[226, 227]
	-	High mechanical characteristics	Road-construction materials	[172]
	low- calcium slag-geopolymer composites	High mechanical characteristics		[158]
Gold	Al_2O_3 -geopolymer composites	High adsorption capacity because of porous structure	Pb2$^+$ adsorbent from aqueous sol	[94,95]
	Al_2O_3 -geopolymer composites	High adsorption capacity because of porous structure		
Gold	BFS-geopolymer composites & metakaolin -geopolymer composites	High mechanical characteristics	Lightweight aggregates	[230]
	fly ash-geopolymer composites	Low water absorption and loose bulk density; large void volume		[3]
Iron	fly ash-geopolymer composites	compressive strength and Improved setting time	Binder materials	[153]
	fly ash-geopolymer composites	Low porosity and microcracking; good thermal resistance		[141]
	Glass wool residue-geopolymer composites	High compressive strength and flexural strength		[139]
	BFS-geopolymer composites & fly ash-geopolymer composites	High compressive and hardness strength; homogeneous structure	Bricks	[247]
	fly ash-geopolymer composites	High adsorption capability; porous structure	Cu^{2+} adsorbent from water	[141]
	-	Low electrical resistance; high compressive strength, low water absorption	Bricks	[148]
	-	High compressive strength	Backfills for building foundations; road-bed material,	[168]
Phosphate	-	High compressive strength	Binder materials	[97]
	fly ash-geopolymer composites & metakaolin -geopolymer composites	density and Mechanical characteristics are both high		
Silica-rich vanadium	fly ash-geopolymer composites	Temperature stability across a wide range	Fire-resistant materials	[165]
Sphalerite	metakaolin -geopolymer composites	Toxic components have a high immobilization ability	Pb^{2+} immobilization	[183]

13. Limitations of the use of mine tailings-geopolymer composites

Despite the advantages of alkali activation of mine tailings, some limitations are outlined below:

1. The processing conditions, which include the temperature, used for curing and mixing methods, as well as the water/binder ratio and raw material composition, affect the final matrix properties.
2. Volume reduction because of loss of water during the drying process leads to drying shrinkage. The nature of materials and mixture proportions determine the quantity of change in the volume.
3. There is also the development of bicarbonate crystals caused by the highly alkaline solution on the surface of the sample with carbon dioxide in the atmosphere. This is termed efflorescence, which can be mitigated by the inclusion of some quantities of active aluminum into the process [248].
4. There is another problem with using by-products from industrial sources as raw materials. Toxic metals can be leached out of them.

14. Conclusions

The key annotations for this paper review are as follows:

1. Mine waste seems to be an attractive option for recovering mine waste and generating sustainable building and construction materials, mine paste backfills, and stabilizing materials for hazardous element immobilization. This strategy not only reduces the carbon footprint of typical cementitious materials, but it also keeps the environment from being harmed by the large amount of waste from mines.
2. Dehydrated tailings are utilized for the manufacturing of geopolymers more frequently than other forms of tailings. Dehydrated tailings are created either by dry tailing operations or by basically drying the mine tailings paste or slurry and subsequently grinding.
3. Mine tailings are often composed of a highly crystalline matrix, which results in minimal interaction throughout geopolymerization and, consequently, a product with low mechanical characteristics. Incorporating extra elements with increased interaction into mine tailings-geopolymer composites may efficiently tune and enhance the characteristics of the geopolymers. Furthermore, since the majority of the additives utilized for this function are industrial by-products, their usage has the additional benefit of reducing the amount of waste produced.
4. Supplemental materials, especially those with a lot of calcium, tend to be better at making geopolymer characteristics. This is caused by the production of more CSH gels, which strengthen the matrix due to its coexistence with NASH, which increases the density of the matrix.
5. The minerals that form mine tailings are identified by their varying chemical reactivity to alkali. The interactions of the precursors' metal components in alkaline conditions affect the structure and characteristics of the geopolymer's aluminosilicate framework.
6. Pre-treatment of mine tailings can be utilized to boost its interaction, and it has been done effectively. This can be accomplished by the utilization of mechanical, thermochemical, and thermal activation techniques that increase the specific surface area of the mine tailings components and transform them into amorphous and soluble states.
7. The increase in interaction after pre-treatment enables a high rate of geopolymerization at an initial phase and higher mechanical characteristics of the cured materials. In addition, the high silica concentration of mine tailings raises the molar proportion of SiO2/Al2O3 in mine tailings-geopolymer composites, impairing the process of geopolymerization. A solution to this difficulty can be found by including additional precursors, like metakaolin or scattered aluminum oxide, into the mix.

8. Among the most successful pre-treatment methods for industrial solid waste, mechanical activation is one of the most effective; for instance, grinding may increase the possible interaction of cement-based materials. The energy needs for wet-grinding and dry-grinding are 1.65 kW and 1.65 kW, respectively, to get rid of the product itself. In light of the fact that mineral comminution accounts for approximately 4–5% of all global electricity consumption, this energy consumption is considerable.

15. Recommendations

The following are the main recommendations for future investigations:

1. Many aspects influence how well mine tailings and geopolymer composites work, and the synergistic effect between some of them (e.g., mineralogy, virtue, elemental distribution) must be addressed in order to reap the greatest possible advantage from the use of mine tailings.
2. When employing mine tailings-geopolymer composites, it is crucial to consider not only their mineralogical, physical, and chemical characteristics but also the possibility of the presence of numerous pollutants, like processing liquids, heavy metals, and other contaminants in their composition. However, the concerns about the movement of these pollutants under the impact of leaching and other processes, in addition to their impact on the attributes of final components derived from mine tailings-geopolymer composites, have received comparatively little attention in the scientific literature. Also, mine tailings can contain natural radionuclides in amounts that exceed the radiological safety criteria. This is something that should be thought about when using mine tailings in geopolymers.
3. Incorporating extra elements with increased interaction into mine tailings-geopolymer composites may efficiently tune and enhance the characteristics of the geopolymers. Therefore, further investigation is recommended in this regard.
4. The interactions of the precursors' metal components in alkaline conditions affect the structure and characteristics of the geopolymer's aluminosilicate framework. Therefore, further investigation is recommended in this regard.
5. Pre-treatment of mine tailings can be utilized to boost their interaction. Therefore, further investigation is recommended in this regard. Besides, It is not clear how mechanical pre-treatment affects the compressive strength of the last geopolymer. This is not as clear as how adding extra materials affects it.
6. Because of the low interaction of native metal trichlorides, the presence of beneficial components ingrained in the minerals initially processed, and the risk of toxic contamination by leaching components, utilizing tailings for geopolymer preparation is prohibitively expensive and time-consuming from an economic and production standpoint. Aspects like the geographic closeness of the mining and processing enterprises to the mine tailings customers as well as the regions where finished geopolymer products are consumed should be taken into consideration when conducting a feasibility study for its application in geopolymer composites.
7. Because of the deficiencies in the past decades' preparation processes, mine tailings accumulating in landfills or tailing piles might contain considerable amounts of unrecoverable precious metals and, as a result, can serve as a viable technological raw material for recycling. If the utilization of metal-comprising tailings is not supplemented by the mining of beneficial components from them, it may be deemed economically unjustifiable. As a result, the concerns of neutralization of contaminants present in tailings and further mining of useful components from mine tailings for their long-term usage in geopolymers need to be addressed.
8. No classification strategy for mine tailings is in place that is based on its interaction. Recent research results, like using the topological technique to measure how glasses interact, can be used to categorize and classify these materials, which will make them easier to use in geopolymerization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] L. Dong, X. Tong, X. Li, J. Zhou, S. Wang, B. Liu, Some developments and new insights of environmental problems and deep mining strategy for cleaner production in mines, J. Clean. Prod. 210 (2019) 1562–1578.
[2] M. Nurcholis, D.F. Yudiantoro, D. Haryanto, A. Mirzam, Heavy metals distribution in the artisanal gold mining area in Wonogiri, Indones. J. Geogr. 49 (2017) 133–144.
[3] N.J. Vickers, Animal communication: when i'm calling you, will you answer too? Curr. Biol. 27 (2017) R713–R715.
[4] W.-h. Zhou, Y.-t. Wang, Z.-h. Lian, T.-t. Yang, Q.-w. Zeng, S.-w. Feng, Z. Fang, W.-s. Shu, L.-n. Huang, Z.-h. Ye, B. Liao, J.-t. Li, Revegetation approach and plant identity unequally affect structure, ecological network and function of soil microbial community in a highly acidified mine tailings pond, Sci. Total Environ. 744 (2020), 140793.
[5] A. Vasile, A.R. Milăşan, A.E. Andrei, R.N. Turcu, M.F. Drăgoescu, S. Axinte, M. Mihaly, An integrated value chain to iron-containing mine tailings capitalization by a combined process of magnetic separation, microwave digestion and microemulsion – assisted extraction, Process Saf. Environ. Protect. 154 (2021) 118–130.
[6] N. Min, J. Yao, M. Amde, L. Wu, G. Sunahara, H. Li, Y. Chen, J. Liu, V.G. Mihucz, Accelerated solvent extraction combined with GC–MS: a convenient technique for the determination and compound-specific stable isotope analysis of phthalates in mine tailings, Microchem. J. 153 (2020), 104366.
[7] D. Komljenovic, L. Stojanovic, V. Malbasic, A. Lukic, A resilience-based approach in managing the closure and abandonment of large mine tailing ponds, Int. J. Min. Sci. Technol. 30 (2020) 737–746.
[8] A.M. Salam, B. Örmeci, P.H. Simms, Determination of optimum polymer dosage for dewatering of oil sands tailings using torque rheology, J. Petrol. Sci. Eng. 197 (2021), 107986.
[9] Z. Li, L. Wang, G. Ma, Chapter 8 - method for the enhancement of buildability and bending resistance of three-dimensional-printable tailing mortar, in: J.G. Sanjayan, A. Nazari, B. Nematollahi (Eds.) 3D Concrete Printing Technology, Butterworth-Heinemann2019, pp. 161-180.
[10] W. Hu, C.L. Xin, Y. Li, Y.S. Zheng, T.W.J. van Asch, M. McSaveney, Instrumented flume tests on the failure and fluidization of tailings dams induced by rainfall infiltration, Eng. Geol. 294 (2021), 106401.
[11] J.E. Galán, The benefits are at the tail: uncovering the impact of macroprudential policy on growth-at-risk, J. Financ. Stabil. (2020), 100831.
[12] L.S. Passos, K.G. Gnocchi, T.M. Pereira, G.C. Coppo, D.S. Cabral, L.C. Gomes, Is the Doce River elutriate or its water toxic to Astyanax lacustris (Teleostei: characidae) three years after the Samarco mining dam collapse? Sci. Total Environ. 736 (2020), 139644.
[13] E.A. Deliyanni, G.Z. Kyzas, K.S. Triantafyllidis, K.A. Matis, Activated carbons for the removal of heavy metal ions: a systematic review of recent literature focused on lead and arsenic ions, Open Chemistry 13 (2015).
[14] J. Schäfer, A. Coynel, G. Blanc, Impact of metallurgy tailings in a major European fluvial-estuarine system: trajectories and resilience over seven decades, Sci. Total Environ. 805 (2022), 150195.
[15] G.d.S. Santos, E.E.C. Silva, G.F. Barroso, V.M.D. Pasa, E.M. Eskinazi-Sant'Anna, Do metals differentiate zooplankton communities in shallow and deep lakes affected by mining tailings? The case of the Fundão dam failure (Brazil), Sci. Total Environ. 806 (2022), 150493.
[16] H.M. Queiroz, S.C. Ying, M. Abernathy, D. Barcellos, F.A. Gabriel, X.L. Otero, G. N. Nóbrega, A.F. Bernardino, T.O. Ferreira, Manganese: the overlooked contaminant in the world largest mine tailings dam collapse, Environ. Int. 146 (2021), 106284.
[17] M. Perrett, B. Sivarajah, C.L. Cheney, J.B. Korosi, L. Kimpe, J.M. Blais, J.P. Smol, Impacts on aquatic biota from salinization and metalloid contamination by gold mine tailings in sub-Arctic lakes, Environ. Pollut. 278 (2021), 116815.
[18] C.E.T. Parente, A.S. Lino, G.O. Carvalho, A.C. Pizzochero, C.E. Azevedo-Silva, M. O. Freitas, C. Teixeira, R.L. Moura, V.J.M. Ferreira Filho, O. Malm, First year after the Brumadinho tailings' dam collapse: spatial and seasonal variation of trace elements in sediments, fishes and macrophytes from the Paraopeba River, Brazil, Environ. Res. 193 (2021), 110526.
[19] V.O.d. Almeida, T.C.B. Pereira, L.d.S. Teodoro, M. Escobar, C.J. Ordovás, K.B. dos Santos, J. Weiler, M.R. Bogo, I.A.H. Schneider, On the effects of iron ore tailings micro/nanoparticles in embryonic and larval zebrafish (Danio rerio), Sci. Total Environ. 759 (2021), 143456.

[20] J. Csavina, J. Field, M.P. Taylor, S. Gao, A. Landázuri, E.A. Betterton, A.E. Sáez, A review on the importance of metals and metalloids in atmospheric dust and aerosol from mining operations, Sci. Total Environ. 433 (2012) 58–73.
[21] W. Zhang, J. Long, X. Zhang, W. Shen, Z. Wei, Pollution and ecological risk evaluation of heavy metals in the soil and sediment around the HTM Tailings Pond, Northeastern China, Int. J. Environ. Res. Publ. Health 17 (2020) 7072.
[22] M. Moradi, Y. You, H. Hung, J. Li, R. Park, N. Alexandrou, S.G. Moussa, L. Jantunen, R. Robitaille, R.M. Staebler, Fugitive emissions of polycyclic aromatic compounds from an oil sands tailings pond based on fugacity and inverse dispersion flux calculations, Environ. Pollut. 269 (2021), 116115.
[23] X. Jiang, W. Liu, H. Xu, X. Cui, J. Li, J. Chen, B. Zheng, Characterizations of heavy metal contamination, microbial community, and resistance genes in a tailing of the largest copper mine in China, Environ. Pollut. 280 (2021), 116947.
[24] L. Jiang, H. Sun, T. Peng, W. Ding, B. Liu, Q. Liu, Comprehensive evaluation of environmental availability, pollution level and leaching heavy metals behavior in non-ferrous metal tailings, J. Environ. Manag. 290 (2021), 112639.
[25] T.M. Carvalho Eugênio, J. Francisco Fagundes, Q. Santos Viana, A. Pereira Vilela, R. Farinassi Mendes, Study on the feasibility of using iron ore tailing (iot) on technological properties of concrete roof tiles, Construct. Build. Mater. 279 (2021), 122484.
[26] P.L. Hageman, P.H. Briggs, A Simple Field Leach Test for Rapid Screening and Qualitative Characterization of Mine Waste Dump Material on Abandoned Mine Lands, US Dept. of the Interior, US Geological Survey, 2000.
[27] Q. Zhai, R. Liu, C. Wang, X. Wen, X. Li, W. Sun, A novel scheme for the utilization of Cu slag flotation tailings in preparing internal electrolysis materials to degrade printing and dyeing wastewater, J. Hazard Mater. 424 (2022), 127537.
[28] T.A.H. Nguyen, Y. Liu, S. Wu, L. Huang, Unravelling in-situ hardpan properties and functions in capping sulfidic Cu-Pb-Zn tailings and forming a duplex soil system cover, J. Hazard Mater. 425 (2022), 127943.
[29] L.-J. Han, J.-S. Li, Q. Xue, M.-Z. Guo, P. Wang, C.S. Poon, Enzymatically induced phosphate precipitation (EIPP) for stabilization/solidification (S/S) treatment of heavy metal tailings, Construct. Build. Mater. 314 (2022), 125577.
[30] Z. Guo, X. Sun, X. Zhang, J. Qiu, H. Jiang, Y. Zhao, P. Wu, Q. Zhang, Effect of superplasticizer on rheology and thixotropy of superfine-tailings cemented paste backfill: experiment and modelling, Construct. Build. Mater. 316 (2022), 125693.
[31] W. Chen, S. Yin, G. Zhou, Z. Li, Q. Song, Copper recovery from tailings through bioleaching and further application of bioleached tailings residue: comprehensive utilization of tailings, J. Clean. Prod. 332 (2022), 130129.
[32] S.M.A. Qaidi, PET-concrete Confinement with CFRP, 2021.
[33] S.M.A. Qaidi, PET-Concrete, 2021.
[34] H.U. Ahmed, A.A. Mohammed, S. Rafiq, A.S. Mohammed, A. Mosavi, N.H. Sor, S. M.A. Qaidi, Compressive strength of sustainable geopolymer concrete composites: a state-of-the-art review, Sustainability 13 (2021), 13502.
[35] S.M.A. Qaidi, B.A. Tayeh, A.M. Zeyad, A.R.G. de Azevedo, H.U. Ahmed, W. Emad, Recycling of mine tailings for the geopolymers production: a systematic review, Case Stud. Constr. Mater. 16 (2022), e00933.
[36] S.M.A. Qaidi, B.A. Tayeh, H.F. Isleem, A.R.G. de Azevedo, H.U. Ahmed, W. Emad, Sustainable utilization of red mud waste (bauxite residue) and slag for the production of geopolymer composites: a review, Case Stud. Constr. Mater. 16 (2022), e00994.
[37] S.M.A. Qaidi, Y.Z. Dinkha, J.H. Haido, M.H. Ali, B.A. Tayeh, Engineering properties of sustainable green concrete incorporating eco-friendly aggregate of crumb rubber: a review, J. Clean. Prod. 324 (2021), 129251.
[38] R.H. Faraj, H.U. Ahmed, S. Rafiq, N.H. Sor, D.F. Ibrahim, S.M.A. Qaidi, Performance of self-compacting mortars modified with nanoparticles: a systematic review and modeling, Cleaner Materials (2022), 100086.
[39] I. Almeshal, M.M. Al-Tayeb, S.M.A. Qaidi, B.H. Abu Bakar, B.A. Tayeh, Mechanical properties of eco-friendly cements-based glass powder in aggressive medium, Mater. Today Proc. 58 (2022) 1582–1587, https://doi.org/10.1016/j.matpr.2022.03.613.
[40] S.N. Ahmed, N. Hamah Sor, M.A. Ahmed, S.M.A. Qaidi, Thermal conductivity and hardened behavior of eco-friendly concrete incorporating waste polypropylene as fine aggregate, Mater. Today Proc. 57 (2022) 818–823.
[41] H.U. Ahmed, A.S. Mohammed, R.H. Faraj, S.M.A. Qaidi, A.A. Mohammed, Compressive strength of geopolymer concrete modified with nano-silica: experimental and modeling investigations, Case Stud. Constr. Mater. 16 (2022), e01036.
[42] S.M.A. Qaidi, Behavior of Concrete Made of Recycled PET Waste and Confined with CFRP Fabrics, College of Engineering, University of Duhok, 2021.
[43] S.M.A. Qaidi, Y.S.S. Al-Kamaki, State-of-the-Art review: concrete made of recycled waste PET as fine aggregate, J. Donghua Univ. 23 (2021) 412–429.
[44] A. Mansi, N.H. Sor, N. Hilal, S.M. Qaidi, The impact of nano clay on normal and high-performance concrete characteristics, in: A Review, IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2022, 012085.
[45] F.A. Jawad Ahmad, Rebeca Martinez-Garcia, Jesús de-Prado-Gil, M. Shaker, A. Qaidi, Ameni Brahmia, Effects of waste glass and waste marble on mechanical and durability performance of concrete, Sci. Rep. 11 (2021), 21525.
[46] M. Rico, G. Benito, A. Salgueiro, A. Díez-Herrero, H. Pereira, Reported tailings dam failures: a review of the European incidents in the worldwide context, J. Hazard Mater. 152 (2008) 846–852.
[47] C.M. Longhini, S.K. Rodrigues, E.S. Costa, C.A. da Silva, R.C. Cagnin, M. Gripp, B. D.C. Lehrback, G.N. Mill, E.M.C. de Oliveira, C.d.C.M. Hermogenes, D.G. F. Rodrigues, A.M. David, K.C. Gramlich, R.d.C. Bisi Júnior, A.A.P. Gomes, J.P. da Silva Filho, J.F. Almeida, K.F. de Souza, W.A.R. Luz Junior, L.M.B. Poleze, R. R. Barros, D. Rigo, R.D. Ghisolfi, R.R. Neto, F. Sá, Environmental quality assessment in a marine coastal area impacted by mining tailing using a geochemical multi-index and physical approach, Sci. Total Environ. 803 (2022), 149883.
[48] J. Lana-Costa, M.M. da Silva, A.O. Martins, J.C. Guarnier, R.d.O. Silva Junior, D. M. Silva, A. Nunes-Nesi, W.L. Araújo, Biochemical and physiological aspects of restinga herbaceous plants tolerance to iron ore tailing plume along the coastal region of Espírito Santo-Brazil, Environ. Exp. Bot. 191 (2021), 104618.
[49] K. Islam, S. Murakami, Global-scale impact analysis of mine tailings dam failures: 1915–2020, Global Environ. Change 70 (2021), 102361.
[50] E.B. Duarte, M.A. Neves, F.B. de Oliveira, M.E. Martins, C.H.R. de Oliveira, D. L. Burak, M.T.D.A. Orlando, C.V.G.T. Rangel, Trace metals in Rio Doce sediments before and after the collapse of the Fundão iron ore tailing dam, Southeastern Brazil, Chemosphere 262 (2021), 127879.
[51] C. dos Santos Vergilio, D. Lacerda, T. da Silva Souza, B.C.V. de Oliveira, V. S. Fioresi, V.V. de Souza, G. da Rocha Rodrigues, M.K. de Araujo Moreira Barbosa, E. Sartori, T.P. Rangel, D.Q.R. de Almeida, M.G. de Almeida, F. Thompson, C. E. de Rezende, Immediate and long-term impacts of one of the worst mining tailing dam failure worldwide (Bento Rodrigues, Minas Gerais, Brazil), Sci. Total Environ. 756 (2021), 143697.
[52] A.C. Cavalheiro Paulelli, C.A. Cesila, P.P. Devóz, S. Ruella de Oliveira, J. P. Bianchi Ximenez, W.d.R. Pedreira Filho, F. Barbosa Jr., Fundão tailings dam failure in Brazil: evidence of a population exposed to high levels of Al, As, Hg, and Ni after a human biomonitoring study, Environ. Res. 205 (2022), 112524.
[53] R.L. Burritt, K.L. Christ, Full cost accounting: a missing consideration in global tailings dam management, J. Clean. Prod. 321 (2021), 129016.
[54] C. Zhang, X. Wang, Z. Hu, Q. Wu, H. Zhu, J. Lu, Long-term performance of silane coupling agent/metakaolin based geopolymer, J. Build. Eng. 36 (2021), 102091.
[55] C. Rodrigue Kaze, A. Adesina, G. Laure Lecomte-Nana, J.V. Sontia Metekong, L. Van Essa Kamga Samen, E. Kamseu, U.C. Melo, Synergetic effect of rice husk ash and quartz sand on microstructural and physical properties of laterite clay based geopolymer, J. Build. Eng. 43 (2021), 103229.
[56] K.M. Klima, K. Schollbach, H.J.H. Brouwers, Q. Yu, Enhancing the thermal performance of Class F fly ash-based geopolymer by sodalite, Construct. Build. Mater. 314 (2022), 125574.
[57] K.V.S. Gopala Krishna Sastry, P. Sahitya, A. Ravitheja, Influence of nano TiO2 on strength and durability properties of geopolymer concrete, Mater. Today Proc. 45 (2021) 1017–1025.
[58] M. Catauro, F. Barrino, S. Pacifico, S. Piccolella, I. Lancellotti, C. Leonelli, Synthesis of WEEE-based geopolymers and their cytotoxicity, Mater. Today Proc. 34 (2021) 121–124.
[59] G. Lazorenko, A. Kasprzhitskii, F. Shaikh, R. Krishna, J. Mishra, Utilization Potential of Mine Tailings in Geopolymers: Part 1. Physicochemical and Environmental Aspects, Process Safety and Environmental Protection, 2021.
[60] S.M.A. Qaidi, Ultra-high-performance Fiber-Reinforced Concrete, Challenges, 2022.
[61] S.M.A. Qaidi, Ultra-high-performance Fiber-Reinforced Concrete, Applications, 2022.
[62] S.M.A. Qaidi, Ultra-high-performance Fiber-Reinforced Concrete, Cost assessment, 2022.
[63] P. Kinnunen, A. Ismailov, S. Solismaa, H. Sreenivasan, M.-L. Räisänen, E. Levänen, M. Illikainen, Recycling mine tailings in chemically bonded ceramics–a review, J. Clean. Prod. 174 (2018) 634–649.
[64] B. Dold, Sourcing of critical elements and industrial minerals from mine waste–The final evolutionary step back to sustainability of humankind? J. Geochem. Explor. (2020), 106638.
[65] S. Divvala, M. Swaroopa Rani, Early strength properties of geopolymer concrete composites: an experimental study, Mater. Today Proc. 47 (2021) 3770–3777.
[66] J. Davidovits, L. Huaman, R. Davidovits, Ancient organo-mineral geopolymer in South-American Monuments: organic matter in andesite stone. SEM and petrographic evidence, Ceram. Int. 45 (2019) 7385–7389.
[67] S. Zhao, M. Xia, L. Yu, X. Huang, B. Jiao, D. Li, Optimization for the preparation of composite geopolymer using response surface methodology and its application in lead-zinc tailings solidification, Construct. Build. Mater. 266 (2021), 120969.
[68] N. Zhang, B. Tang, X. Liu, Cementitious activity of iron ore tailing and its utilization in cementitious materials, bricks and concrete, Construct. Build. Mater. 288 (2021), 123022.
[69] N. Zhang, A. Hedayat, H.G. Bolaños Sosa, N. Tupa, I. Yanqui Morales, R. S. Canahua Loza, Mechanical and fracture behaviors of compacted gold mine tailings by semi-circular bending tests and digital image correlation, Construct. Build. Mater. 306 (2021), 124841.
[70] N. Zhang, A. Hedayat, H.G. Bolaños Sosa, R.P. Huamani Bernal, N. Tupa, I. Yanqui Morales, R.S. Canahua Loza, On the incorporation of class F fly-ash to enhance the geopolymerization effects and splitting tensile strength of the gold mine tailings-based geopolymer, Construct. Build. Mater. 308 (2021), 125112.
[71] N. Zhang, A. Hedayat, H.G. Bolaños Sosa, J.J. González Cárdenas, G.E. Salas Álvarez, V.B. Ascuña Rivera, Specimen size effects on the mechanical behaviors and failure patterns of the mine tailings-based geopolymer under uniaxial compression, Construct. Build. Mater. 281 (2021), 122525.
[72] G. Xue, E. Yilmaz, G. Feng, S. Cao, Bending behavior and failure mode of cemented tailings backfill composites incorporating different fibers for sustainable construction, Construct. Build. Mater. 289 (2021), 123163.
[73] Y. Wang, Z. Li, Q. Jin, M. Zhang, Z. Zhou, High-efficiency utilization of limestone tailings: used as cementitious materials and fine aggregate to prepare karst structure filling material, Construct. Build. Mater. 316 (2022), 125841.
[74] V. Mymrin, D.E. Pedroso, C.L. Pedroso, M.A. Avanci, P.H.B. Rolim, K.Q. Carvalho, R.E. Catai, Physical-chemical processes of sustainable construction materials

structure formation with iron ore processing tailings and aluminum anodizing sludge, Construct. Build. Mater. 298 (2021), 123698.
[75] X. Kong, L. Dai, Y. Wang, D. Qiao, S. Hou, S. Wang, Influence of kenaf stalk on printability and performance of 3D printed industrial tailings based geopolymer, Construct. Build. Mater. (2021), 125787.
[76] C. Ince, S. Derogar, K. Gurkaya, R.J. Ball, Properties, durability and cost efficiency of cement and hydrated lime mortars reusing copper mine tailings of Lefke-Xeros in Cyprus, Construct. Build. Mater. 268 (2021), 121070.
[77] A. Barzegar Ghazi, A. Jamshidi-Zanjani, H. Nejati, Utilization of copper mine tailings as a partial substitute for cement in concrete construction, Construct. Build. Mater. 317 (2022), 125921.
[78] A.M.T. Bagger, W. Kunther, N.M. Sigvardsen, P.E. Jensen, Screening for key material parameters affecting early-age and mechanical properties of blended cementitious binders with mine tailings, Case Stud. Constr. Mater. 15 (2021), e00608.
[79] J. Kiventerä, P. Perumal, J. Yliniemi, M. Illikainen, Mine tailings as a raw material in alkali activation: a review, International Journal of Minerals, Metallurgy and Materials 27 (2020) 1009–1020.
[80] Yliniemi, Paiva, Ferreira, Illikainen Tiainen, Development and incorporation of lightweight waste-based geopolymer aggregates in mortar and concrete, Construct. Build. Mater. 131 (2017) 784–792.
[81] P. Perumal, K. Piekkari, H. Sreenivasan, P. Kinnunen, M. Illikainen, One-part geopolymers from mining residues – effect of thermal treatment on three different tailings, Miner. Eng. 144 (2019), 106026.
[82] E.M. Opiso, C.B. Tabelin, C.V. Maestre, J.P.J. Aseniero, I. Park, M. Villacorte-Tabelin, Synthesis and characterization of coal fly ash and palm oil fuel ash modified artisanal and small-scale gold mine (ASGM) tailings based geopolymer using sugar mill lime sludge as Ca-based activator, Heliyon 7 (2021), e06654.
[83] S. Moukannaa, M. Loutou, M. Benzaazoua, L. Vitola, J. Alami, R. Hakkou, Recycling of phosphate mine tailings for the production of geopolymers, J. Clean. Prod. 185 (2018) 891–903.
[84] E. Arioz, O. Arioz, O.M. Kockar, Leaching of F-type fly ash based geopolymers, Procedia Eng. 42 (2012) 1114–1120.
[85] R.S. Krishna, J. Mishra, M. Zribi, F. Adeniyi, S. Saha, S. Baklouti, F.U.A. Shaikh, H.S. Gökçe, A review on developments of environmentally friendly geopolymer technology, Materialia 20 (2021), 101212.
[86] S. Ahmari, L. Zhang, Utilization of cement kiln dust (CKD) to enhance mine tailings-based geopolymer bricks, Construct. Build. Mater. 40 (2013) 1002–1011.
[87] J.S. van Deventer, J.L. Provis, P. Duxson, D.G. Brice, Chemical research and climate change as drivers in the commercial adoption of alkali activated materials, Waste and Biomass Valorization 1 (2010) 145–155.
[88] J.L. Provis, J.S.J. Van Deventer, Geopolymers: Structures, Processing, Properties and Industrial Applications, Elsevier2009.
[89] G. Lazorenko, A. Kasprzhitskii, V. Yavna, V. Mischinenko, A. Kukharskii, A. Kruglikov, A. Kolodina, G. Yalovega, Effect of pre-treatment of flax tows on mechanical properties and microstructure of natural fiber reinforced geopolymer composites, Environ. Technol. Innovat. 20 (2020), 101105.
[90] G. Lazorenko, A. Kasprzhitskii, A. Kruglikov, V. Mischinenko, V. Yavna, Sustainable geopolymer composites reinforced with flax tows, Ceram. Int. 46 (2020) 12870–12875.
[91] A. Hassan, M. Arif, M. Shariq, Use of geopolymer concrete for a cleaner and sustainable environment–A review of mechanical properties and microstructure, J. Clean. Prod. 223 (2019) 704–728.
[92] M. Chau-Khun, A.A. Zawawi, O. Wahid, Structural and Material Performance of Geopolymer Concrete 2018, ELSEVIER, 2018.
[93] S. T, K.R. P R, S. M, S.A. J R, A state-of-the-art on development of geopolymer concrete and its field applications, Case Stud. Constr. Mater. 16 (2022), e00812.
[94] F. Demir, E. Moroydor Derun, Usage of gold mine tailings based geopolymer on Cu 2+ adsorption from water, Main Group Chem. 18 (2019) 467–476.
[95] F. Demir, E.M. Derun, Modelling and optimization of gold mine tailings based geopolymer by using response surface method and its application in Pb2+ removal, J. Clean. Prod. 237 (2019), 117766.
[96] A.A. Siyal, M.R. Shamsuddin, M.I. Khan, N.E. Rabat, M. Zulfiqar, Z. Man, J. Siame, K.A. Azizli, A review on geopolymers as emerging materials for the adsorption of heavy metals and dyes, J. Environ. Manag. 224 (2018) 327–339.
[97] S. Moukannaa, A. Nazari, A. Bagheri, M. Loutou, J. Sanjayan, R. Hakkou, Alkaline fused phosphate mine tailings for geopolymer mortar synthesis: thermal stability, mechanical and microstructural properties, J. Non-Cryst. Solids 511 (2019) 76–85.
[98] N. Zhang, A. Hedayat, H.G. Bolaños Sosa, N. Tupa, I. Yanqui Morales, R. S. Canahua Loza, Crack evolution in the Brazilian disks of the mine tailings-based geopolymers measured from digital image correlations: an experimental investigation considering the effects of class F fly ash additions, Ceram. Int. 47 (2021) 32382–32396.
[99] A.R. de Azevedo, M. Teixeira Marvila, L. Barbosa de Oliveira, W. Macario Ferreira, H. Colorado, S. Rainho Teixeira, C. Mauricio Fontes Vieira, Circular Economy and Durability in Geopolymers Ceramics Pieces Obtained from Glass Polishing Waste, International Journal of Applied Ceramic Technology, 2021.
[100] N. Ouffa, M. Benzaazoua, T. Belem, R. Trauchessec, A. Lecomte, Alkaline dissolution potential of aluminosilicate minerals for the geosynthesis of mine paste backfill, Mater. Today Commun. 24 (2020), 101221.
[101] M. Amin, A.M. Zeyad, B.A. Tayeh, I.S. Agwa, Effect of high temperatures on mechanical, radiation attenuation and microstructure properties of heavyweight geopolymer concrete, Struct. Eng. Mech. 80 (2021) 181–199.
[102] M.M. Ahmed, K. El-Naggar, D. Tarek, A. Ragab, H. Sameh, A.M. Zeyad, B. A. Tayeh, I.M. Maafa, A. Yousef, Fabrication of thermal insulation geopolymer bricks using ferrosilicon slag and alumina waste, Case Stud. Constr. Mater. 15 (2021), e00737.
[103] A.L. Almutairi, B.A. Tayeh, A. Adesina, H.F. Isleem, A.M. Zeyad, Potential applications of geopolymer concrete in construction: a review, Case Stud. Constr. Mater. 15 (2021), e00733.
[104] N. Zhang, A. Hedayat, H.G. Bolaños Sosa, R.P. Huamani Bernal, N. Tupa, I. Yanqui Morales, R.S. Canahua Loza, Fracture properties of the gold mine tailings-based geopolymer under mode I loading condition through semi-circular bend tests with digital image correlation, Theor. Appl. Fract. Mech. 116 (2021), 103116.
[105] N. Zhang, A. Hedayat, H.G. Bolaños Sosa, J.J. González Cárdenas, G.E. Salas Álvarez, V.B. Ascuña Rivera, Damage evaluation and deformation behavior of mine tailing-based Geopolymer under uniaxial cyclic compression, Ceram. Int. 47 (2021) 10773–10785.
[106] A.R.G. de Azevedo, M.T. Marvila, M. Ali, M.I. Khan, F. Masood, C.M.F. Vieira, Effect of the addition and processing of glass polishing waste on the durability of geopolymeric mortars, Case Stud. Constr. Mater. 15 (2021), e00662.
[107] M.T. Marvila, A.R.G.d. Azevedo, C.M.F. Vieira, Reaction Mechanisms of Alkali-Activated Materials, vol. 14, Revista IBRACON de Estruturas e Materiais, 2021.
[108] A.R.G. de Azevedo, M.T. Marvila, H.A. Rocha, L.R. Cruz, C.M.F. Vieira, Use of glass polishing waste in the development of ecological ceramic roof tiles by the geopolymerization process, Int. J. Appl. Ceram. Technol. 17 (2020) 2649–2658.
[109] S.M.A. Qaidi, Ultra-high-performance Fiber-Reinforced Concrete: Durability Properties, 2022.
[110] S.M.A. Qaidi, Ultra-high-performance Fiber-Reinforced Concrete: Hardened Properties, 2022.
[111] S.M.A. Qaidi, Ultra-high-performance Fiber-Reinforced Concrete: Fresh Properties, 2022.
[112] C. Anning, J. Wang, P. Chen, I. Batmunkh, X. Lyu, Determination and detoxification of cyanide in gold mine tailings: a review, Waste Manag. Res. 37 (2019) 1117–1126.
[113] I. Park, C.B. Tabelin, S. Jeon, X. Li, K. Seno, M. Ito, N. Hiroyoshi, A review of recent strategies for acid mine drainage prevention and mine tailings recycling, Chemosphere 219 (2019) 588–606.
[114] G. Lazorenko, A. Kasprzhitskii, F. Shaikh, R.S. Krishna, J. Mishra, Utilization potential of mine tailings in geopolymers: physicochemical and environmental aspects, Process Saf. Environ. Protect. 147 (2021) 559–577.
[115] A. Davidovits, Geopolymers: inorganic polymeric new materials, J. Therm. Anal. 37 (1991) 1633–1656.
[116] H.U. Ahmed, A.A. Mohammed, S. Rafiq, A.S. Mohammed, A. Mosavi, N.H. Sor, S. Qaidi, Compressive strength of sustainable geopolymer concrete composites: a state-of-the-art review, Sustainability 13 (2021), 13502.
[117] P. Duxson, A. Fernández-Jiménez, J.L. Provis, G.C. Lukey, A. Palomo, J.S. van Deventer, Geopolymer technology: the current state of the art, J. Mater. Sci. 42 (2007) 2917–2933.
[118] W. Mozgawa, J. Deja, Spectroscopic studies of alkaline activated slag geopolymers, J. Mol. Struct. 924–926 (2009) 434–441.
[119] H. Yan, X. Zhu, F. Dai, Y. He, X. Jing, P. Song, R. Wang, Porous geopolymer based eco-friendly multifunctional slow-release fertilizers for promoting plant growth, Colloids Surf. A Physicochem. Eng. Asp. 631 (2021), 127646.
[120] E.E. Sánchez Díaz, V.A. Escobar Barrios, Development and use of geopolymers for energy conversion: an overview, Construct. Build. Mater. 315 (2022), 125774.
[121] Y. Qin, X. Chen, B. Li, Y. Guo, Z. Niu, T. Xia, W. Meng, M. Zhou, Study on the mechanical properties and microstructure of chitosan reinforced metakaolin-based geopolymer, Construct. Build. Mater. 271 (2021), 121522.
[122] S.M.A. Qaidi, Ultra-high-performance Fiber-Reinforced Concrete: Hydration and Microstructure, 2022.
[123] S.M.A. Qaidi, Ultra-high-performance Fiber-Reinforced Concrete: Mixture Design, 2022.
[124] S.M.A. Qaidi, Ultra-high-performance Fiber-Reinforced Concrete: Principles and Raw Materials, 2022.
[125] P. Zhang, K. Wang, Q. Li, J. Wang, Y. Ling, Fabrication and engineering properties of concretes based on geopolymers/alkali-activated binders-A review, J. Clean. Prod. 258 (2020), 120896.
[126] Z. Wang, H. Wu, Y. Xu, K. Shu, J. Yang, L. Luo, L. Xu, Effect of dissolved fluorite and barite species on the flotation and adsorption behavior of bastnaesite, Separ. Purif. Technol. 237 (2020), 116387.
[127] L. Wei, M. Sun, Numerical studies of the influence of particles' size distribution characteristics on the gravity separation performance of Liquid-solid Fluidized Bed Separator, Int. J. Miner. Process. 157 (2016) 111–119.
[128] X. Chen, X. Shi, J. Zhou, X. Du, Q. Chen, X. Qiu, Effect of overflow tailings properties on cemented paste backfill, J. Environ. Manag. 235 (2019) 133–144.
[129] D. Kossoff, W. Dubbin, M. Alfredsson, S. Edwards, M. Macklin, K.A. Hudson-Edwards, Mine tailings dams: characteristics, failure, environmental impacts, and remediation, Appl. Geochem. 51 (2014) 229–245.
[130] T. Assawincharoenkij, C. Hauzenberger, C. Sutthirat, Mineralogy and geochemistry of tailings from a gold mine in northeastern Thailand, Human and Ecological Risk Assessment, Int. J. 23 (2017) 364–387.
[131] K. Hudson-Edwards, H. Jamieson, B. Lottermoser, Mine wastes: past, present, future, Elements 7 (2011) 375–380.
[132] H. Xu, J. Van Deventer, The geopolymerisation of alumino-silicate minerals, Int. J. Miner. Process. 59 (2000) 247–266.
[133] J. Ye, W. Zhang, D. Shi, Properties of an aged geopolymer synthesized from calcined ore-dressing tailing of bauxite and slag, Cement Concr. Res. 100 (2017) 23–31.

[134] J. Ye, W. Zhang, D. Shi, Effect of elevated temperature on the properties of geopolymer synthesized from calcined ore-dressing tailing of bauxite and ground-granulated blast furnace slag, Construct. Build. Mater. 69 (2014) 41–48.
[135] X. Li, P. Wang, Z. Guo, J. Qin, K. Liang, Effect of Fe2+/Fe3+ on high-strength ceramsite prepared by sintering geopolymers using iron ore tailings, Ceram. Int. (2021).
[136] P. Duan, C. Yan, W. Zhou, D. Ren, Fresh properties, compressive strength and microstructure of fly ash geopolymer paste blended with iron ore tailing under thermal cycle, Construct. Build. Mater. 118 (2016) 76–88.
[137] P. Duan, C. Yan, W. Zhou, D. Ren, Development of fly ash and iron ore tailing based porous geopolymer for removal of Cu(II) from wastewater, Ceram. Int. 42 (2016) 13507–13518.
[138] K. do Carmo e Silva Defáveri, L.F. dos Santos, J.M. Franco de Carvalho, R.A. F. Peixoto, G.J. Brigolini, Iron ore tailing-based geopolymer containing glass wool residue: a study of mechanical and microstructural properties, Construct. Build. Mater. 220 (2019) 375–385.
[139] L.F. dos Santos, J.M.F. de Carvalho, R.A.F. Peixoto, G.J. Brigolini, Iron ore tailing-based geopolymer containing glass wool residue: a study of mechanical and microstructural properties, Construct. Build. Mater. 220 (2019) 375–385.
[140] B. Sternal, J. Junttila, K. Skirbekk, M. Forwick, J. Carroll, K.B. Pedersen, The impact of submarine copper mine tailing disposal from the 1970s on Repparfjorden, northern Norway, Mar. Pollut. Bull. 120 (2017) 136–153.
[141] P. Duan, C. Yan, W. Zhou, D. Ren, Development of fly ash and iron ore tailing based porous geopolymer for removal of Cu (II) from wastewater, Ceram. Int. 42 (2016) 13507–13518.
[142] G. Cao, W. Wang, G. Yin, Z. Wei, Experimental study of shear wave velocity in unsaturated tailings soil with variant grain size distribution, Construct. Build. Mater. 228 (2019), 116744.
[143] Y. Haddaji, H. Majdoubi, S. Mansouri, Y. Tamraoui, M. El bouchti, B. Manoun, M. Oumam, H. Hannache, Effect of synthetic fibers on the properties of geopolymers based on non-heat treated phosphate mine tailing, Mater. Chem. Phys. 260 (2021), 124147.
[144] V.F.F. Barbosa, K.J.D. MacKenzie, Thermal behaviour of inorganic geopolymers and composites derived from sodium polysialate, Mater. Res. Bull. 38 (2003) 319–331.
[145] J. Schön, Physical Properties of Rocks: A workbook, Elsevier2011.
[146] G. Mudd, D. Boger, The ever growing case for paste and thickened tailings—towards more sustainable mine waste management, J. Aust. Inst. Min. Metall 2 (2013) 56–59.
[147] M.B. Lindsay, M.C. Moncur, J.G. Bain, J.L. Jambor, C.J. Ptacek, D.W. Blowes, Geochemical and mineralogical aspects of sulfide mine tailings, Appl. Geochem. 57 (2015) 157–177.
[148] F.A. Kuranchie, S.K. Shukla, D. Habibi, Utilisation of iron ore mine tailings for the production of geopolymer bricks, Int. J. Min. Reclamat. Environ. 30 (2016) 92–114.
[149] L. Yu, Z. Zhang, X. Huang, B. Jiao, D. Li, Enhancement experiment on cementitious activity of copper-mine tailings in a geopolymer system, Fibers 5 (2017) 47.
[150] B. Wei, Y. Zhang, S. Bao, Preparation of geopolymers from vanadium tailings by mechanical activation, Construct. Build. Mater. 145 (2017) 236–242.
[151] H. Cheng, C. Chen, S. Wu, Z.A. Mirza, Z. Liu, Emergy evaluation of cropping, poultry rearing, and fish raising systems in the drawdown zone of Three Gorges Reservoir of China, J. Clean. Prod. 144 (2017) 559–571.
[152] N. Niroshan, L. Yin, N. Sivakugan, R.L. Veenstra, Relevance of SEM to long-term mechanical properties of cemented paste backfill, Geotech. Geol. Eng. 36 (2018) 2171–2187.
[153] B. Sharath, K. Shivaprasad, M. Athikkal, B. Das, Some studies on sustainable utilization of iron ore tailing (IOT) as fine aggregates in fly ash based geopolymer mortar, in: IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2018, 092010.
[154] A. Sahi, K. El Mahboub, T. Belem, A. Maqsoud, M. Mbonimpa, Dewatering of mine tailings slurries using superabsorbent polymers (SAPs) reclaimed from industrial reject of baby diapers: a preliminary study, Minerals 9 (2019) 785.
[155] H. Paiva, J. Yliniemi, M. Illikainen, F. Rocha, V.M. Ferreira, Mine tailings geopolymers as a waste management solution for a more sustainable habitat, Sustainability 11 (2019) 995.
[156] A.M.T. Simonsen, S. Solismaa, H.K. Hansen, P.E. Jensen, Evaluation of mine tailings' potential as supplementary cementitious materials based on chemical, mineralogical and physical characteristics, Waste Manag. 102 (2020) 710–721.
[157] Y. Wu, B. Lu, T. Bai, H. Wang, F. Du, Y. Zhang, L. Cai, C. Jiang, W. Wang, Geopolymer, green alkali activated cementitious material: synthesis, applications and challenges, Construct. Build. Mater. 224 (2019) 930–949.
[158] L. Manjarrez, A. Nikvar-Hassani, R. Shadnia, L. Zhang, Experimental study of geopolymer binder synthesized with copper mine tailings and low-calcium copper slag, J. Mater. Civ. Eng. 31 (2019), 04019156.
[159] M. Gitari, S. Akinyemi, R. Thobakgale, P. Ngoejana, L. Ramugondo, M. Matidza, S. Mhlongo, F. Dacosta, N. Nemapate, Physicochemical and mineralogical characterization of Musina mine copper and New Union gold mine tailings: implications for fabrication of beneficial geopolymeric construction materials, J. Afr. Earth Sci. 137 (2018) 218–228.
[160] T. Falayi, A comparison between fly ash-and basic oxygen furnace slag-modified gold mine tailings geopolymers, International Journal of Energy and Environmental Engineering (2019) 1–11.
[161] J. Kiventerä, H. Sreenivasan, C. Cheeseman, P. Kinnunen, M. Illikainen, Immobilization of sulfates and heavy metals in gold mine tailings by sodium silicate and hydrated lime, J. Environ. Chem. Eng. 6 (2018) 6530–6536.
[162] H. Niu, M. Abdulkareem, H. Sreenivasan, A.M. Kantola, J. Havukainen, M. Horttanainen, V.-V. Telkki, P. Kinnunen, M. Illikainen, Recycling mica and carbonate-rich mine tailings in alkali-activated composites: a synergy with metakaolin, Miner. Eng. 157 (2020), 106535.
[163] J. Park, B. Lee, W. Shin, S. Jo, H. Jun, Psychrophilic methanogenesis of food waste in a bio-electrochemical anaerobic digester with rotating impeller electrode, J. Clean. Prod. 188 (2018) 556–567.
[164] Y. Luo, S. Bao, Y. Zhang, Preparation of one-part geopolymeric precursors using vanadium tailing by thermal activation, J. Am. Ceram. Soc. 103 (2020) 779–783.
[165] X. Jiao, Y. Zhang, T. Chen, Thermal stability of a silica-rich vanadium tailing based geopolymer, Construct. Build. Mater. 38 (2013) 43–47.
[166] P. Perumal, K. Piekkari, H. Sreenivasan, P. Kinnunen, M. Illikainen, One-part geopolymers from mining residues–Effect of thermal treatment on three different tailings, Miner. Eng. 144 (2019), 106026.
[167] A. Wang, H. Liu, X. Hao, Y. Wang, X. Liu, Z. Li, Geopolymer synthesis using garnet tailings from molybdenum mines, Minerals 9 (2019) 48.
[168] J. McDonald, S. Roache, S. Kawatra, Repurposing mine tailings: cold bonding of siliceous iron ore tailings, Miner. Metall. Process. 33 (2016) 47–52.
[169] M. Song, L. Jiaping, J. Qian, L. Jianzhong, S. Liang, Experimental study on utilization of quartz mill tailings as a filler to prepare geopolymer, Miner. Process. Extr. Metall. Rev. 37 (2016) 311–322.
[170] Q. Wan, F. Rao, S. Song, C.A. Leon-Patino, Y. Ma, W. Yin, Consolidation of mine tailings through geopolymerization at ambient temperature, J. Am. Ceram. Soc. 102 (2019) 2451–2461.
[171] G. Kastiukas, X. Zhou, J. Castro-Gomes, Preparation conditions for the synthesis of alkali-activated binders using tungsten mining waste, J. Mater. Civ. Eng. 29 (2017), 04017181.
[172] L. Manjarrez, L. Zhang, Utilization of copper mine tailings as road base construction material through geopolymerization, J. Mater. Civ. Eng. 30 (2018), 04018201.
[173] X. Tian, W. Xu, S. Song, F. Rao, L. Xia, Effects of curing temperature on the compressive strength and microstructure of copper tailing-based geopolymers, Chemosphere 253 (2020), 126754.
[174] P. Duan, C. Yan, W. Zhou, W. Luo, Fresh properties, mechanical strength and microstructure of fly ash geopolymer paste reinforced with sawdust, Construct. Build. Mater. 111 (2016) 600–610.
[175] C. Qi, A. Fourie, Cemented paste backfill for mineral tailings management: review and future perspectives, Miner. Eng. 144 (2019), 106025.
[176] Z. Xiaolong, Z. Shiyu, L. Hui, Z. Yingliang, Disposal of mine tailings via geopolymerization, J. Clean. Prod. 284 (2021), 124756.
[177] 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.
[178] M. Edraki, T. Baumgartl, E. Manlapig, D. Bradshaw, D.M. Franks, C.J. Moran, Designing mine tailings for better environmental, social and economic outcomes: a review of alternative approaches, J. Clean. Prod. 84 (2014) 411–420.
[179] J. Kiventerä, L. Golek, J. Yliniemi, V. Ferreira, J. Deja, M. Illikainen, Utilization of sulphidic tailings from gold mine as a raw material in geopolymerization, Int. J. Miner. Process. 149 (2016) 104–110.
[180] L. Weber, T. Leek, A. Alzubairi, An Economic Analysis of the Extraction of Rare Earth Elements from WPPA Sand Tailings Waste Stream, 2015.
[181] Y.M. Amran, R. Alyousef, H. Alabduljabbar, M. El-Zeadani, Clean production and properties of geopolymer concrete; A review, J. Clean. Prod. 251 (2020), 119679.
[182] J. Davidovits, Geopolymers: ceramic-like inorganic polymers, J. Ceram. Sci. Technol 8 (2017) 335–350.
[183] Q. Wan, F. Rao, S. Song, Y. Zhang, Immobilization forms of ZnO in the solidification/stabilization (S/S) of a zinc mine tailing through geopolymerization, J. Mater. Res. Technol. 8 (2019) 5728–5735.
[184] N. Marjanović, M. Komljenović, Z. Baščarević, V. Nikolić, Improving reactivity of fly ash and properties of ensuing geopolymers through mechanical activation, Construct. Build. Mater. 57 (2014) 151–162.
[185] Ł. Kotwica, M. Chorembała, E. Kapeluszna, P. Stępień, J. Deja, M. Illikainen, Ł. Gołek, Influence of Calcined Mine Tailings on the Properties of Alkali Activated Slag Mortars, Key Engineering Materials, Trans Tech Publ, 2018, pp. 83–86.
[186] H.T. Kouamo, J. Mbey, A. Elimbi, B.K. Diffo, D. Njopwouo, Synthesis of volcanic ash-based geopolymer mortars by fusion method: effects of adding metakaolin to fused volcanic ash, Ceram. Int. 39 (2013) 1613–1621.
[187] L. Tchadjié, J. Djobo, N. Ranjbar, H. Tchakouté, B.D. Kenne, A. Elimbi, D. Njopwouo, Potential of using granite waste as raw material for geopolymer synthesis, Ceram. Int. 42 (2016) 3046–3055.
[188] D. Zhang, C.-H. Zhou, C.-X. Lin, D.-S. Tong, W.-H. Yu, Synthesis of clay minerals, Appl. Clay Sci. 50 (2010) 1–11.
[189] X. Ren, L. Zhang, D. Ramey, B. Waterman, S. Ormsby, Utilization of aluminum sludge (AS) to enhance mine tailings-based geopolymer, J. Mater. Sci. 50 (2015) 1370–1381.
[190] O. Ozcan, H. Benzer, Comparison of different breakage mechanisms in terms of product particle size distribution and mineral liberation, Miner. Eng. 49 (2013) 103–108.
[191] M. Gou, L. Zhou, N.W.Y. Then, Utilization of tailings in cement and concrete: a review, Sci. Eng. Compos. Mater. 26 (2019) 449–464.
[192] R. Argane, M. Benzaazoua, R. Hakkou, A. Bouamrane, A comparative study on the practical use of low sulfide base-metal tailings as aggregates for rendering and masonry mortars, J. Clean. Prod. 112 (2016) 914–925.
[193] W. Xu, X. Wen, J. Wei, P. Xu, B. Zhang, Q. Yu, H. Ma, Feasibility of kaolin tailing sand to be as an environmentally friendly alternative to river sand in construction applications, J. Clean. Prod. 205 (2018) 1114–1126.

[194] G.N. Eujine, S. Chandrakaran, N. Sankar, Accelerated subgrade stabilization using enzymatic lime technique, J. Mater. Civ. Eng. 29 (2017), 04017085.
[195] A.B. Akinyemi, E.T. Omoniyi, G. Onuzulike, Effect of microwave assisted alkali pretreatment and other pretreatment methods on some properties of bamboo fibre reinforced cement composites, Construct. Build. Mater. 245 (2020), 118405.
[196] H. Savastano Jr., V. Agopyan, A.M. Nolasco, L. Pimentel, Plant fibre reinforced cement components for roofing, Construct. Build. Mater. 13 (1999) 433–438.
[197] T. Luukkonen, Z. Abdollahnejad, J. Yliniemi, P. Kinnunen, M. Illikainen, One-part alkali-activated materials: a review, Cement Concr. Res. 103 (2018) 21–34.
[198] P. Perumal, J. Kiventerä, M. Illikainen, Influence of alkali source on properties of alkali activated silicate tailings, Mater. Chem. Phys. 271 (2021), 124932.
[199] S. Kelham, A water absorption test for concrete, Mag. Concr. Res. 40 (1988) 106–110.
[200] P. Duan, C. Yan, W. Zhou, W. Luo, C. Shen, An investigation of the microstructure and durability of a fluidized bed fly ash–metakaolin geopolymer after heat and acid exposure, Mater. Des. 74 (2015) 125–137.
[201] S. Aydın, C.Ç. Kızıltepe, Valorization of boron mine tailings in alkali-activated mortars, J. Mater. Civ. Eng. 31 (2019), 04019224.
[202] S.A. Bernal, R.M. de Gutiérrez, A.L. Pedraza, J.L. Provis, E.D. Rodriguez, S. Delvasto, Effect of binder content on the performance of alkali-activated slag concretes, Cement Concr. Res. 41 (2011) 1–8.
[203] M. Falah, R. Obenaus-Emler, P. Kinnunen, M. Illikainen, Effects of activator properties and curing conditions on alkali-activation of low-alumina mine tailings, Waste and Biomass Valorization 11 (2020) 5027–5039.
[204] Z. Zhang, J.L. Provis, A. Reid, H. Wang, Geopolymer foam concrete: an emerging material for sustainable construction, Construct. Build. Mater. 56 (2014) 113–127.
[205] M. Falah, K. Ohenoja, R. Obenaus-Emler, P. Kinnunen, M. Illikainen, Improvement of mechanical strength of alkali-activated materials using micro low-alumina mine tailings, Construct. Build. Mater. 248 (2020), 118659.
[206] N. Ghafoori, M. Najimi, B. Radke, Natural Pozzolan-based geopolymers for sustainable construction, Environ. Earth Sci. 75 (2016) 1–16.
[207] P. Perumal, H. Niu, J. Kiventerä, P. Kinnunen, M. Illikainen, Upcycling of mechanically treated silicate mine tailings as alkali activated binders, Miner. Eng. 158 (2020), 106587.
[208] E. Barrie, V. Cappuyns, E. Vassilieva, R. Adriaens, S. Hollanders, D. Garcés, C. Paredes, Y. Pontikes, J. Elsen, L. Machiels, Potential of inorganic polymers (geopolymers) made of halloysite and volcanic glass for the immobilisation of tailings from gold extraction in Ecuador, Appl. Clay Sci. 109 (2015) 95–106.
[209] P.H. Ribeiro Borges, F.C. Resende Ramos, T. Rodrigues Caetano, T. Hallak Panzerra, H. Santos, Reuse of Iron Ore Tailings in the Production of Geopolymer Mortars, Revista Escola de Minas, Rem, 2019, p. 72.
[210] X. Zhu, W. Li, Z. Du, S. Zhou, Y. Zhang, F. Li, Recycling and utilization assessment of steel slag in metakaolin based geopolymer from steel slag by-product to green geopolymer, Construct. Build. Mater. 305 (2021), 124654.
[211] O. Mahmoodi, H. Siad, M. Lachemi, M. Sahmaran, Synthesis and optimization of binary systems of brick and concrete wastes geopolymers at ambient environment, Construct. Build. Mater. 276 (2021), 122217.
[212] O. Mahmoodi, H. Siad, M. Lachemi, S. Dadsetan, M. Sahmaran, Development of optimized binary ceramic tile and concrete wastes geopolymer binders for in-situ applications, J. Build. Eng. 43 (2021), 102906.
[213] O. Mahmoodi, H. Siad, M. Lachemi, S. Dadsetan, M. Sahmaran, Development of normal and very high strength geopolymer binders based on concrete waste at ambient environment, J. Clean. Prod. 279 (2021), 123436.
[214] G. Liang, H. Zhu, H. Li, T. Liu, H. Guo, Comparative study on the effects of rice husk ash and silica fume on the freezing resistance of metakaolin-based geopolymer, Construct. Build. Mater. 293 (2021), 123486.
[215] S. Gomes, L. Frezet, E. Petit, S. Petlickaia, S. Rossignol, N. Texier-Mandoki, G. Renaudin, Temperature stability of an argillite/K-geopolymer composite: impact of argillite filler on dimensional behavior, Open Ceramics 5 (2021), 100081.
[216] L. Tchadjie, S. Ekolu, Enhancing the reactivity of aluminosilicate materials toward geopolymer synthesis, J. Mater. Sci. 53 (2018) 4709–4733.
[217] L.N. Tchadjié, S.O. Ekolu, H. Quainoo, P. Tematio, Incorporation of activated bauxite to enhance engineering properties and microstructure of volcanic ash geopolymer mortar composites, J. Build. Eng. 41 (2021), 102384.
[218] G. Mucsi, S. Kumar, B. Csőke, R. Kumar, Z. Molnár, Á. Rácz, F. Mádai, Á. Debreczeni, Control of geopolymer properties by grinding of land filled fly ash, Int. J. Miner. Process. 143 (2015) 50–58.
[219] S. Kushwah, M. Mudgal, R.K. Chouhan, The Process, Characterization and Mechanical properties of fly ash-based Solid form geopolymer via mechanical activation, S. Afr. J. Chem. Eng. 38 (2021) 104–114.
[220] S. Kumar, G. Mucsi, F. Kristály, P. Pekker, Mechanical activation of fly ash and its influence on micro and nano-structural behaviour of resulting geopolymers, Adv. Powder Technol. 28 (2017) 805–813.
[221] S. Kumar, R. Kumar, Mechanical activation of fly ash: effect on reaction, structure and properties of resulting geopolymer, Ceram. Int. 37 (2011) 533–541.
[222] A.D. Hounsi, G.L. Lecomte-Nana, G. Djétéli, P. Blanchart, Kaolin-based geopolymers: effect of mechanical activation and curing process, Construct. Build. Mater. 42 (2013) 105–113.
[223] A.Z. Khalifa, Ö. Cizer, Y. Pontikes, A. Heath, P. Patureau, S.A. Bernal, A.T. Marsh, Advances in alkali-activation of clay minerals, Cement Concr. Res. 132 (2020), 106050.
[224] M. Falah, R. Obenaus-Emler, P. Kinnunen, M. Illikainen, Effects of activator properties and curing conditions on alkali-activation of low-alumina mine tailings, Waste and Biomass Valorization (2019) 1–13.
[225] S. Ahmari, L. Zhang, Durability and leaching behavior of mine tailings-based geopolymer bricks, Construct. Build. Mater. 44 (2013) 743–750.
[226] S. Ahmari, X. Ren, V. Toufigh, L. Zhang, Production of geopolymeric binder from blended waste concrete powder and fly ash, Construct. Build. Mater. 35 (2012) 718–729.
[227] S. Ahmari, L. Zhang, J. Zhang, Effects of activator type/concentration and curing temperature on alkali-activated binder based on copper mine tailings, J. Mater. Sci. 47 (2012) 5933–5945.
[228] T. Falayi, Effect of potassium silicate and aluminate on the stabilisation of gold mine tailings, Proceedings of the Institution of Civil Engineers-Waste and Resource Management (2019) 56–63. Thomas Telford Ltd.
[229] W. Pardavé, M. Epalza, J. Durán, D.F. Lóvera, Obtaining A cementitious geopolymer from gold mining tailings with possible use in engineering applications, American Journal of Engineering Research (AJER) 7 (2018) 137–142.
[230] J. Kiventerä, J. Yliniemi, L. Golek, J. Deja, V. Ferreira, M. Illikainen, Utilization of Sulphidic Mine Tailings in Alkali-Activated Materials, MATEC Web of Conferences, EDP Sciences, 2019, 01001.
[231] S. Solismaa, A. Ismailov, M. Karhu, H. Sreenivasan, M. Lehtonen, P. Kinnunen, M. Illikainen, M.L. Räisänen, Valorization of Finnish Mining Tailings for Use in the Ceramics Industry, vol. 90, Bulletin of the Geological Society of Finland, 2018.
[232] J. Ye, W. Zhang, D. Shi, Performance evolutions of tailing-slag-based geopolymer under severe conditions, Journal of Sustainable Cement-Based Materials 4 (2015) 101–115.
[233] Y. Haddaji, H. Majdoubi, S. Mansouri, Y. Tamraoui, B. Manoun, M. Oumam, H. Hannache, Effect of synthetic fibers on the properties of geopolymers based on non-heat treated phosphate mine tailing, Mater. Chem. Phys. 260 (2021), 124147.
[234] S. Ahmari, L. Zhang, Production of eco-friendly bricks from copper mine tailings through geopolymerization, Construct. Build. Mater. 29 (2012) 323–331.
[235] S. Ahmari, K. Parameswaran, L. Zhang, Alkali activation of copper mine tailings and low-calcium flash-furnace copper smelter slag, J. Mater. Civ. Eng. 27 (2015), 04014193.
[236] L. Zhang, S. Ahmari, J. Zhang, Synthesis and characterization of fly ash modified mine tailings-based geopolymers, Construct. Build. Mater. 25 (2011) 3773–3781.
[237] J. Kiventerä, I. Lancellotti, M. Catauro, F. Dal Poggetto, C. Leonelli, M. Illikainen, Alkali activation as new option for gold mine tailings inertization, J. Clean. Prod. 187 (2018) 76–84.
[238] Q. Yuan, C. Shi, G. De Schutter, K. Audenaert, D. Deng, Chloride binding of cement-based materials subjected to external chloride environment–a review, Construct. Build. Mater. 23 (2009) 1–13.
[239] F. El Meski, G. Chehab, Flexural behavior of concrete beams reinforced with different types of geogrids, J. Mater. Civ. Eng. 26 (2014), 04014038.
[240] X. Jiao, Y. Zhang, T. Chen, S. Bao, T. Liu, J. Huang, Geopolymerisation of a silica-rich tailing, Miner. Eng. 24 (2011) 1710–1712.
[241] E. Caballero, W. Sánchez, C.A. Ríos, Synthesis of geopolymers from alkaline activation of gold mining wastes, Ingeniería y competitividad 16 (2014) 317–330.
[242] G. Liang, H. Zhu, Z. Zhang, Q. Wu, Effect of rice husk ash addition on the compressive strength and thermal stability of metakaolin based geopolymer, Construct. Build. Mater. 222 (2019) 872–881.
[243] H.Y. Zhang, G.H. Qiu, V. Kodur, Z.S. Yuan, Spalling behavior of metakaolin-fly ash based geopolymer concrete under elevated temperature exposure, Cement Concr. Compos. 106 (2020), 103483.
[244] M.K. LeFauve, V.P. Connaughton, Developmental exposure to heavy metals alters visually-guided behaviors in zebrafish, Current zoology 63 (2017) 221–227.
[245] Z. Ren, L. Wang, Y. Li, J. Zha, G. Tian, F. Wang, H. Zhang, J. Liang, Synthesis of zeolites by in-situ conversion of geopolymers and their performance of heavy metal ion removal in wastewater:A review, J. Clean. Prod. 349 (2022), 131441.
[246] S. Hu, L. Zhong, X. Yang, H. Bai, B. Ren, Y. Zhao, W. Zhang, X. Ju, H. Wen, S. Mao, Synthesis of rare earth tailing-based geopolymer for efficiently immobilizing heavy metals, Construct. Build. Mater. 254 (2020), 119273.
[247] R. Kumar, P. Das, M. Beulah, H. Arjun, G. Ignatius, Utilization of iron ore tailings for the production of fly ash—GGBS-based geopolymer bricks, J. Adv. Manuf. Syst. 16 (2017) 275–290.
[248] E.N. Kani, A. Allahverdi, J.L. Provis, Efflorescence control in geopolymer binders based on natural pozzolan, Cement Concr. Compos. 34 (2012) 25–33.