





Review

A Comprehensive Review on Mine Tailings as a Raw Material in the Alkali Activation Process

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Abstract: The mining industry generates vast quantities of mine tailings on an annual basis. However, due to their limited economic value, a significant portion of these tailings are deposited close to mining sites, often underwater. The principal environmental apprehensions associated with mine tailings revolve around their elevated levels of heavy metals and sulfidic minerals. The oxidation of these sulfidic minerals can lead to the formation of acid mine drainage, which in turn releases heavy metals into nearby water systems. The effective management of tailing dams requires substantial financial investments for their construction and meticulous control. Consequently, a pressing need exists for stable, sustainable, and economically viable management approaches. One promising method for addressing mine tailings is through alkali activation, a technique that serves as a stabilization process. This approach yields robust, concrete-like structures by utilizing raw materials abundant in aluminum and silicon, which conveniently constitute the primary components of mining residues. This comprehensive review outlines the research on utilizing alkali activation for mine tailings. It delves into the reactivity and chemical attributes of diverse minerals. Numerous mine tailings exhibit an inadequate level of reactivity under alkaline conditions, so various pre-treatment methodologies and their impacts on mineralogy are meticulously explored.

Keywords: mine tailings; sustainability; alkali activation; mechanical activation; thermal treatment; alkaline fusion



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1. Introduction

Construction is indispensable for the growth, development, and well-being of societies. It shapes their physical, economic, and social landscapes, leaving a lasting impact on generations to come [1]. In recent years, there has been a growing focus on recycling and repurposing waste materials to mitigate environmental impacts and promote sustainable practices within the construction industry [2,3]. Mine tailings are the waste materials left over after valuable minerals and metals have been extracted from mined ore through various processes. These tailings are composed of finely ground rock, water, and leftover chemicals used in the extraction and processing of minerals and are typically disposed of in tailing storage facilities or tailing dams [4].

During the mining process, rocks and minerals are excavated from the Earth's crust, often containing valuable minerals and metals, such as gold, copper, silver, or iron [5]. They undergo processing to separate the valuable components from the surrounding waste rock by crushing, grinding, chemical treatments, and other methods to extract the desired minerals [6]. The leftover materials that remain after the valuable minerals have been extracted are known as mine tailings. A substantial portion of the materials (estimated to

range from 97 wt% to 99 wt%) extracted from mining operations end up as mine tailings [7]. This percentage can vary depending on the type of mining, the ore being extracted, and the efficiency of the extraction process. The mentioned estimate indicates that only a tiny fraction of the original material is converted into valuable minerals. The rest, making up the majority of the material, becomes waste in the form of tailings. The estimated annual solid mine waste production is 20–35 billion tons, which includes 7–14 billion tons of mine tailings, underscoring the scale of the waste produced by mining operations worldwide [8].

The composition of mine tailings can vary widely depending on the type of ore being mined and the extraction methods used. Tailings can contain minerals, heavy metals, and processing chemicals. The size of the particles can range from fine silt to larger gravel-sized particles [9]. The Earth's crust is primarily composed of a few abundant elements like silicon, aluminum, calcium iron, sodium, and potassium, making mine tailings theoretically suitable as a raw material for construction purposes [10].

The poor reactivity of minerals within tailings can make it difficult to extract valuable components or repurpose the tailings effectively. Mine tailings often consist of minerals undergoing extensive processing during mining operations. This processing can alter the minerals' original crystalline structures and chemical compositions, making them less reactive to traditional extraction or reprocessing methods [11]. Moreover, the valuable minerals in mine tailings are usually present in low concentrations, which further compounds the challenge. Even if the minerals are reactive, their low abundance might not make extraction or recovery economically viable [12].

The fine particle size of tailings can affect their reactivity. Smaller particles can be harder to process due to issues such as agglomeration, handling difficulties, and challenges in separating minerals from one another. Furthermore, the processing chemicals used during the initial extraction can sometimes lead to changes in the mineralogy of tailings, resulting in the formation of new minerals or mineral phases that are less amenable to extraction [13].

Many mine tailings can contain high concentrations of sulfur, heavy metals, and metalloids since the valuable metals extracted from ores are frequently found within sulfidic minerals. Sulfidic minerals are minerals that contain sulfur combined with other elements, often including valuable metals such as copper, zinc, lead, and nickel [14]. These metals are chemically bonded to the sulfur within the minerals. In addition to sulfur, mine tailings can contain elevated levels of heavy metals, such as lead, copper, zinc, and cadmium, and metalloids such as arsenic. When the tailings are exposed to the environment, these elements can leach out and contaminate soil and water, posing serious environmental and health risks [15,16]. The sulfur in sulfidic minerals becomes concentrated in the resulting mine tailings. When these tailings are exposed to air and water, sulfur-containing compounds can undergo oxidation reactions, producing sulfuric acid and contributing to acid mine drainage (AMD), which is a critical environmental issue associated with mine tailing management and poses significant challenges during the active mining phase and after a mine has been closed [17].

The presence of sulfidic minerals and high concentrations of heavy metals in mine tailings can hinder their recycling potential, and the effective safety management of hazardous mine tailings is essential. Improper handling or inadequate containment can result in safety risks to surrounding communities. Tailings dams, if not constructed and appropriately managed, can pose significant risks and can lead to catastrophic events. Researchers actively seek innovative solutions to mitigate the challenges associated with sulfidic minerals, heavy metals, and tailing management by developing materials and processes that can safely immobilize or utilize these components [18].

Mine tailings are typically stored in tailing storage facilities, which have specially designed areas to contain and manage these waste materials. Tailing dams are constructed to hold the tailings in place, and they are often built using earthen embankments and containment structures. Since certain mine tailings are not considered hazardous waste, the option of reusing or recycling them stands out as an appealing alternative to disposing

of them in landfills [19]. Using mine tailings as a component of backfilling operations is a common approach in the mining industry. Backfilling is a technique used in mining in which voids or underground spaces created by mining activities are filled with suitable materials. This serves various purposes, providing stability to underground workings and preventing subsidence [20]. Tailings, which are often already in a slurry form due to the processing methods used during mineral extraction, can be mixed with other binding materials, such as cement, to create a paste-like substance that can be used as a backfill material in underground mining operations [21]. The final properties of paste backfill material in mining operations are influenced by a combination of factors, including the physical, chemical, and mineralogical characteristics of the tailings, the properties of the co-binder, such as cement or other binding agents, and the water content [22]. The particle size distribution, particle shape, and density of the tailings play a role in determining the overall stability and strength of the paste. Moreover, the chemical composition of the tailings, especially the presence of sulfides and heavy metals, can affect the reactivity and potential environmental impacts of the paste [23]. The types of minerals present in the tailings influence the overall behavior of the paste, including its strength, reactivity, and long-term stability. Furthermore, the choice of co-binder, often cement, affects the setting and hardening of the paste, and the amount of co-binder used in the mixture influences the mechanical properties and setting time of the paste [24]. Also, the ratio of water to solid components in the paste affects its workability, setting time, and strength when aiming to achieve the desired consistency and performance [25].

Within paste backfill technology and the stabilization of mine tailings, the prevalent choice for a binding agent is Portland cement (including cement, lime, and other calcium-containing materials) [26,27]. Nevertheless, the production of Portland cement results in significant CO₂ emissions, making it suboptimal for employment in paste backfilling [28]. Furthermore, in cases in which mine tailings possess the potential to generate acid, utilizing cement-based paste backfilling is not appropriate due to the adverse impact of the resulting acid on the formed matrix. On the other hand, the utilization of pozzolanic products in paste backfill technology is a notable approach that can enhance the properties and sustainability of the backfill material. Pozzolanic materials, such as blast furnace slag or fly ash, react with calcium hydroxide in the presence of water to form cementitious compounds, adding to the strength and durability of the mixture and offering enhanced acid resistance [29].

Since cement-based stabilization may not always be the optimal approach for mine tailings, an alternative strategy for repurposing mining waste is to utilize the tailings as a raw material in alkali activation to create an environmentally friendly construction material for subsequent use [30]. Alkali activation is a stabilization method that is particularly effective with raw materials rich in silicon and aluminum and relies on the reaction between alkaline solutions (often sodium or potassium hydroxide) and source materials containing silicon and aluminum. These elements are essential for the formation of the three-dimensional network of linked mineral compounds known as geopolymers. The raw material, which is rich in silicon and aluminum, is mixed with an alkaline solution, typically containing sodium hydroxide (NaOH) or potassium hydroxide (KOH), serving as an activator for the reaction and raising the pH of the mixture, making it highly alkaline [31]. The high-pH environment triggers the dissolution of silicon (Si) and aluminum (Al) components from the raw material. These elements are released as ions into the solution, undergo a complex series of chemical reactions, and combine with hydroxide ions from the alkaline solution to form new compounds, such as aluminosilicate gel, which is the basis of the three-dimensional network structure of the geopolymer [32]. In the newly formed aluminosilicate gel, the silicon and aluminum atoms are linked together through shared oxygen atoms, similar to how cement particles in traditional concrete are connected through calcium silicate hydrate (C-S-H) bonds [33]. Materials activated through alkali processes exhibit enhanced mechanical properties, a robust level of durability, and resistance to acids and thermal fluctuations [34]. Alkali-activated material shows the ability to immobilize hazardous components such as

heavy metals within their structure, significantly contributing to environmental protection and the safe management of waste materials [35].

Mine tailings, especially those generated from the extraction of metal ores, have gained significant attention as potential precursors in alkali activation due to their abundant content of silicon and aluminum, which are essential elements for the formation of the geopolymeric structure through the alkali activation process [36–38]. One critical challenge associated with using mine tailings in alkali activation processes is the low reactivity of these materials, and it can vary depending on factors such as mineralogical composition, particle size distribution, pre-treatment, and chemical characteristics [39]. Mine tailings with poor reactivity can still be valuable as a filler material when paired with the appropriate co-binder. This approach allows for the utilization of tailings in construction applications while addressing their reactivity limitations. To deploy mine tailings as a reactive material in alkali activation, enhancing the reactivity of the minerals contained within them is essential [40]. Mechanical activation methods, such as grinding, thermal treatment (calcination), and alkaline fusion, are effective in increasing the reactivity of minerals, including those found in mine tailings [41]. These processes modify their mineral structure and composition, making them more amenable to subsequent chemical reactions, such as alkali activation or the formation of geopolymers. Within alkali activation technologies, the resulting materials have versatile applications, including use in paste backfilling, as construction materials at mining sites, or for designing dry landfill alternatives, rather than being discarded in tailing dams [42].

This paper aims to provide a comprehensive review of recent research focused on the alkali activation of mine tailings. Since mine tailings are considered waste, and waste-based materials typically face limitations in large-scale applications, it is necessary to establish laws and policies that facilitate the integration of tailings into construction industries. However, before such policies can be enacted, it is crucial to accumulate sufficient data regarding the practical utilization of mine tailings in construction.

2. Mineralogy of Mine Tailings

The mineralogy of mine tailings can vary widely depending on the type of ore being mined, the processing methods used, and the geological characteristics of the deposit [43]. The mineral phases in mine tailings can be categorized into two main groups: primary phases (reacted and unreacted) and secondary phases (precipitated and weathered). These distinctions are crucial for understanding the mineralogical evolution of mine tailings and their potential environmental impact, as shown in Figure 1. Unreacted primary phases are the mineral phases that originally existed in the ore or rock being mined [44]. These minerals remain largely unchanged during the milling and processing of the ore. Examples include quartz, feldspar, and primary sulfide minerals like pyrite, chalcopyrite, and sphalerite. Reacted primary phases are mineral phases that have undergone some degree of alteration or reaction during the mining and milling process, such as sulfide minerals that may oxidize to form secondary sulfate minerals like jarosite or goethite due to air and water exposure [45]. During precipitated secondary phases, these secondary mineral phases form after the deposition of tailings into the environment. They often result from chemical reactions between tailings, water, and other environmental factors. Examples include the precipitation of iron or aluminum hydroxides (e.g., ferrihydrite and gibbsite) due to changes in pH conditions. Furthermore, weathered secondary phases can alter tailings over time. For example, exposure to rainwater and temperature fluctuations can lead to the leaching of soluble components, the transformation of minerals, and the formation of new weathering products, like clay minerals or iron oxides.

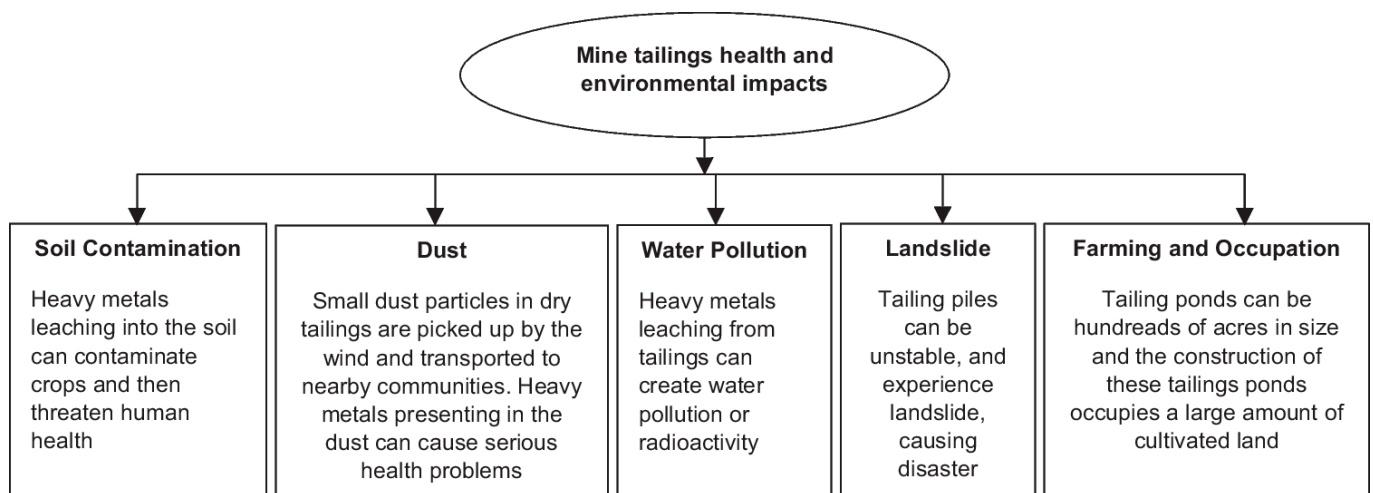


Figure 1. Health and environmental impacts of mine tailings [46].

The comprehensive characterization of fresh and weathered mine tailing materials is essential for thoroughly understanding their material properties and behavior. In order to develop an effective waste management plan, it is essential to study the mineralogy, chemical composition, and potential behavior of the tailings under various environmental conditions [47]. The chemical compositions of various mine tailings are demonstrated in Table 1.

The variability in the elemental composition of mine tailings from different mining sites presents a significant challenge for their standardized use in the construction industry. A multifaceted approach can be implemented to address this issue by focusing on characterization, classification, treatment, and regulatory guidelines. X-ray fluorescence (XRF) and X-ray diffraction (XRD) tests could be conducted to determine the exact composition of the tailings. Developing a classification system based on the chemical and physical properties of tailings can categorize them into different types, each suitable for specific construction applications. In some cases, thermal treatments can alter the physical and chemical properties of tailings, making them more suitable for use in construction. Regulatory guidelines and standards for using mine tailings in construction will help to ensure their safety and performance. By implementing these strategies, the variability in the elemental composition of mine tailings can be managed, allowing for their standardized and safe use in construction applications.

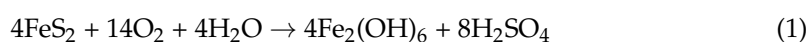
Minerals are fundamental components of the Earth's crust, and they play a vital role in geological processes, the formation of rocks, and the development of natural resources. They are naturally occurring, inorganic solids that possess specific chemical compositions and atomic arrangements, leading to unique crystal structures.

Table 1. The chemical compositions of various mine tailings.

Mine Tailings	Country	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	P ₂ O ₅	V ₂ O ₃	V ₂ O ₅	SO ₂	TiO ₂	SO ₃	ZnO	MnO	CuO	BaO	PbO	LOIa	Others	Ref.
Copper	China	58.5	10.8	13.3	5.4	1.9	2.8	4.0	-	-	-	-	-	0.6	-	-	-	-	-	-	-	[48]
	USA	55.8	3.07	14.11	2.27	1.77	3.02	3.88	0.19	-	-	2.26	0.50	-	-	0.067	-	-	-	-	-	[49]
	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	[50]
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	[51]
	Turkey	89.22	0.84	6.2	-	0.29	-	1.24	-	-	-	-	-	0.09	-	-	-	-	-	-	-	[52]
	Finland	49.9	9.2	10.4	11.8	6.8	-	1.2	-	-	-	-	1.2	-	-	-	-	-	-	13.6	-	[53]
Phosphate	Finland	32.98	7.98	7.08	12.92	17.28	-	5.53	0.96	-	-	-	0.27	-	-	0.12	-	-	-	14.01	0.88	[54]
	Morocco	22.8	0.85	2.5	34.3	4.1	0.9	0.4	14.0	-	-	-	-	-	-	-	-	-	-	19	-	[55]
Iron	Brazil	40.0	48.9	8.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6	1.8	[56]
	Australia	57.30	25.12	9.57	0.03	0.07	0.05	0.04	-	-	-	-	0.61	0.16	-	-	-	-	-	6.67	-	[57]
Vanadium	China	61.92	4.13	7.35	6.52	1.24	2.68	1.25	-	-	0.42	-	0.46	7.15	-	-	-	-	-	6.93	-	[58]
Kaolinite	Finland	72.55	1.90	16.44	0.05	0.83	0.08	3.06	-	-	-	-	-	-	-	-	-	-	-	4.42	0.74	[59]
Lead–zinc	China	62.09	2.73	4.35	20.45	0.56	-	0.55	-	-	-	-	0.2	3.63	-	-	-	-	-	-	-	[60]
Hematite	USA	68.77	28.13	0.87	0.28	0.74	0.03	0.04	-	-	-	-	0.05	-	-	-	0.001	0.02	-	-	0.07	[61]
Lithium	Finland	78.45	0.51	12.56	0.30	0.15	4.44	2.81	-	-	-	-	-	-	-	-	-	-	-	0.2	0.58	[56]
Bauxite	China	32.25	8.66	37.39	3.16	0.85	0.86	-	-	-	-	-	2.31	-	-	-	-	-	-	13.74	-	[62]
Quartz	China	97.48	0.30	1.11	0.17	0.22	0.04	0.02	-	-	-	-	-	-	-	-	-	-	-	-	-	[63]
Tungsten	Portugal	47.85	9.97	21.07	0.85	1.01	1.32	4.12	-	-	-	-	0.66	8.73	-	-	-	-	-	-	-	[64]
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	[65]
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	-	[65]

In the Earth's crust, minerals are classified into four major classes based on their chemical composition [66]. (1) Silicate minerals are the most abundant class of minerals in the Earth's crust and are composed primarily of silicon (Si) and oxygen (O) atoms combined with various cations (positively charged ions), such as aluminum (Al), iron (Fe), magnesium (Mg), and others. Silicate minerals include feldspars, quartz, micas, amphiboles, and pyroxenes [67]. (2) Carbonate minerals are characterized by the carbonate ion (CO_3^{2-}) as a fundamental building block. They are primarily composed of carbon, oxygen, and various cations. Common carbonate minerals include calcite and dolomite [68]. (3) Oxide minerals are primarily composed of oxygen (O) combined with metal cations. These minerals often form as a result of the weathering of other minerals. Oxide minerals include magnetite, hematite, and cassiterite. (4) Sulfide minerals are composed of sulfur (S) combined with metal cations. These minerals often form in hydrothermal environments and are associated with ore deposits [69]. Common sulfide minerals include pyrite, galena, and chalcopyrite.

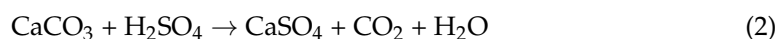
Valuable metals, including gold (Au), copper (Cu), lead (Pb), and zinc (Zn), are commonly found in sulfide minerals. The mining industry extracts these valuable metals from sulfide ores, and as a result, a significant portion of mine tailings generated in mining operations are sulfur-rich [70]. However, this also poses environmental challenges. When sulfide minerals are exposed to air and water during mining operations or in tailing storage facilities, they can oxidize, producing sulfuric acid and releasing metals into the environment [71]. Pyrite, often called "fool's gold", is one of the most common sulfide minerals found on Earth and is widely distributed in various geological environments. The oxidation of pyrite (iron disulfide, FeS_2) involves the reaction of pyrite with oxygen (O_2) and water (H_2O) to produce sulfuric acid (H_2SO_4) and iron oxide (Fe_2O_3). The chemical reaction is represented by Equation (1) as follows:



In this reaction, pyrite (FeS_2) reacts with oxygen (O_2) from the air and water (H_2O) and produces iron hydroxide ($\text{Fe}_2(\text{OH})_6$) as a solid product and sulfuric acid (H_2SO_4) as a solution in water. This process produces acid mine drainage (AMD) when pyrite-containing rocks are exposed to air and water during mining operations [72].

The bioavailability of hazardous components in mine tailings is influenced by a complex interplay of factors, including the oxidation state of elements, mineralogy of tailings, grain size and surface area, morphology, chemical composition, environmental conditions, microbial activity, and hydraulic conditions [73]. When the leaching of harmful components from mine tailings surpasses the legally defined limits for waste, these tailings are classified as hazardous. When such tailings are disposed of in tailing ponds, extensive landfill spaces, along with meticulous construction and ongoing maintenance, are necessary, even after the closure of the mining operation.

Carbonates (e.g., calcite and dolomite) and silicates (e.g., feldspars and olivine) are minerals that can neutralize acidic conditions in tailing ponds and should be characterized to understand the environmental behavior of mine tailings. They are used as neutralizing agents to mitigate the effects of acid mine drainage (AMD) [74]. Calcite (calcium carbonate, CaCO_3) is highly effective in neutralizing acid due to its reaction with acidic water. The reaction can be represented by Equation (2) as follows:



The above reaction represents the neutralization of sulfuric acid (H_2SO_4) by calcium carbonate (CaCO_3), resulting in the formation of gypsum (CaSO_4), carbon dioxide (CO_2), and water (H_2O). Dolomite (calcium magnesium carbonate, $\text{CaMg}(\text{CO}_3)_2$) is similar to calcite but contains calcium and magnesium ions, providing a buffering capacity [75].

Feldspars are aluminosilicate minerals that can react with acidic solutions. The aluminum (Al) and silicon (Si) in their structure can neutralize acidic conditions. Olivine

(magnesium iron silicate, $(\text{Mg, Fe})_2\text{SiO}_4$) is another silicate mineral that can neutralize acid; the reaction involves the release of magnesium and iron ions, which can help buffer against acid [76].

Carbonates can provide the short-term neutralization of acidic conditions by decreasing the acidity of water by raising the pH and decreasing the concentration of hydrogen ions (H^+), while silicates are considered more long-lasting neutralization minerals [77,78]. These minerals, when present in tailings or added as amendments, can help to reduce the risk of environmental damage associated with acid mine drainage [79].

3. Alkali Activation

Alkali activation creates new construction materials from silicon- and aluminum-rich raw materials by mixing these raw materials with a highly alkaline solution. This solution, typically an alkali hydroxide or silicate, serves as an activator. It increases the pH of the mixture and facilitates the formation of a new 3D concrete-like structure. Various elements like iron (Fe), magnesium (Mg), and calcium (Ca) can also play crucial roles in the reaction. These elements contribute to the formation of calcium–(sodium) aluminosilicate hydrate (C(N)ASH), which is a complex amorphous gel-like structure with cementitious properties, similar to the products of cement hydration in ordinary Portland cement and Mg–Al-layered double hydroxide, which can contribute to the mechanical properties and stability of the resulting material. Alkali-activated mine tailing concrete and mortar show a promising level of durability against aggressive ions such as chlorides and sulfates. The durability of these materials can be influenced by the type of activator used, the mix design, and the curing conditions [80]. In terms of chloride resistance, the high alumina and silica content in mine tailings, when activated, can form a dense and chemically stable matrix, reducing the permeability of the concrete or mortar and limiting chloride ingress. The choice of activator (e.g., sodium hydroxide or sodium silicate) affects the pore structure and binding phases, producing more amorphous aluminosilicate gels that tend to enhance chloride resistance. Moreover, proper curing is crucial for developing a dense microstructure that improves chloride penetration resistance. Regarding sulfate resistance, alkali-activated materials often exhibit better levels of resistance than ordinary Portland cement (OPC) due to the absence of calcium hydroxide, which reacts with sulfates to form expansive compounds like ettringite. Meanwhile, incorporating supplementary materials, such as fly ash or slag, can further improve sulfate resistance by refining the pore structure and reducing permeability [81]. When the calcium content is low in alkali-activated materials (AAMs), they are called geopolymers. Geopolymers are a subset of AAMs with distinct characteristics and are defined as inorganic, amorphous to semi-crystalline aluminosilicate materials formed by the reaction of a source material rich in silicon and aluminum with an alkaline activator. Geopolymers, like other AAMs, form a three-dimensional structure through a process known as polycondensation. This results in a network of linked silicon and aluminum atoms [82]. The resulting 3D structure of geopolymers can vary in crystallinity. Some geopolymers may have a poorly crystalline structure, while others may exhibit more crystalline characteristics, depending on the specific raw materials and curing conditions used [83]. Geopolymers often possess excellent mechanical properties, high levels of resistance to chemical attack, and good levels of thermal stability. They also offer sustainability benefits similar to those of other AAMs, including the use of industrial by-products and waste materials, reduced carbon emissions, and lower energy consumption during production. These properties of alkali-activated materials (AAMs) position them as a more sustainable alternative to traditional construction materials like ordinary Portland cement (OPC) [84,85].

The choice of raw materials in alkali activation depends on their reactivity and composition. Among the various aluminosilicate materials suitable for alkali activation, metakaolin and blast furnace slag have received an extensive amount of attention and research [86]. The properties of the alkaline activator play a crucial role in determining the final structure and properties of alkali-activated materials (AAMs). A higher alkalinity

promotes more robust reactions and leads to the formation of a denser and stronger structure, and higher concentration can accelerate the activation process, potentially leading to faster setting times and higher early strength development [87]. The most common types of alkaline reagents used as activators in alkali activation processes are hydroxides (e.g., sodium hydroxide and potassium hydroxide) and silicates (e.g., sodium silicate). Sodium hydroxide (NaOH) is a strong alkaline compound, is highly soluble in water, and provides a significant source of hydroxide ions (OH^-) for the activation process. Potassium hydroxide (KOH) shares properties similar to NaOH, and like NaOH, KOH provides hydroxide ions to drive activation reactions. Sodium silicate (Na_2SiO_4) is an alkaline compound derived from the reaction of sodium carbonate and silica sand, providing both alkalinity and a source of reactive silicon, making it a versatile activator for alkali-activated materials [88].

Alkali-activated materials (AAMs) can immobilize harmful components like heavy metals due to their unique chemical and mechanical properties. AAMs have a robust chemical structure formed through polycondensation reactions between silicon (Si) and aluminum (Al) in the aluminosilicate raw materials. This structure is resistant to chemical breakdown, providing a stable matrix for encapsulating heavy metals [89]. The reactive sites within the AAMs' 3D structure can undergo ion exchange reactions. Heavy metal ions can bind to these sites, displacing other cations, and some heavy metals can be adsorbed onto the surfaces of AAM particles. Moreover, during the activation process, chemical reactions can lead to the formation of low-solubility phases. These phases can incorporate heavy metal ions, effectively immobilizing them within the material [90]. AAMs have good mechanical properties, so they can physically encapsulate heavy metal particles or ions within their structure, preventing their release into the surrounding environment. Finally, the chemical and physical properties of AAMs can reduce the leachability of heavy metals, which means that even under conditions in which an AAM is exposed to water, the release of heavy metals is minimized [91]. When different co-binder materials are introduced, the immobilization mechanism becomes more complex because each co-binder material may have its own chemical properties, which can lead to various interactions with heavy metals. When multiple co-binders are used together, their synergistic effects can enhance the immobilization process; the presence of multiple co-binders introduces heterogeneity to the mixture, making it more challenging to predict and analyze the immobilization process [92]. Co-binders can have different particle sizes and shapes, which affect their accessibility to heavy metals and the overall immobilization efficiency. Furthermore, the pH and redox conditions of the environment can influence how co-binders interact with heavy metals. These conditions can vary depending on factors such as local geology, water chemistry, and microbial activity [93–95]. Finally, alkali activation technology is a promising alternative to traditional Portland cement, but its practical application faces the following challenges: (1) The properties of alkali-activated materials are highly dependent on the source and composition of raw materials, such as fly ash, slag, and other industrial by-products, leading to inconsistent performance. (2) Design mixes for alkali-activated materials are challenging due to the lack of standardized guidelines and the need for the precise control of the activator concentration, water content, and curing conditions. (3) Alkali-activated materials can have excellent levels of durability, but there are concerns related to alkali–aggregate reactions, sulfate attack, and carbonation. More research is needed to fully understand and mitigate these issues. (4) Alkaline activators, such as sodium hydroxide and sodium silicate, are caustic and require careful handling. This poses safety risks and requires specific storage and handling protocols. (5) The cost and availability of suitable raw materials and activators can vary regionally. In some areas, the raw materials needed for alkali activation might not be available or could be more expensive than traditional materials. (6) Comprehensive life cycle assessments (LCAs) and long-term performance data are needed to fully understand the sustainability and durability of alkali-activated materials over extended periods.

3.1. Alkali-Activated Mine Tailings

Mine tailings are a by-product of the mining industry, and their proper handling, disposal, and reuse are essential aspects of responsible mining practices to obtain various benefits, such as those shown in Figure 2. Testing the solubility of different elements in raw materials for alkali activation is crucial to understanding their reactivity. This procedure is a common method used to assess reactivity. After the reaction period, the solution is collected and analyzed using inductively coupled plasma spectrometry (ICP), which is a highly sensitive analytical method that can determine the concentrations of various elements in a sample [96]. These data help us understand which elements are readily available for reactions and incorporation into the final alkali-activated material. Elements that exhibit a high level of solubility under alkaline conditions are considered more reactive [97].



Figure 2. Benefits of recycling and reusing mine tailings [98].

Assessing the crystalline structure of a material through X-ray diffraction (XRD) and scanning electron microscopy (SEM) is another crucial method for estimating its reactivity. XRD provides information about the material's crystalline phases and their relative abundance, while SEM provides detailed images of the material's microstructure and surface morphology [99,100]. Despite the abundance of silicon and aluminum in most mine tailings, their reactivity under alkaline conditions can be limited due to the highly crystalline structure of many mine tailings. The minerals in mine tailings often have well-defined crystalline structures. This means their atoms are arranged in a repeating pattern, which can resist dissolution and chemical reactions. Moreover, in highly crystalline materials, the surface atoms may be less chemically active compared to those in amorphous or poorly crystalline phases, reducing the likelihood of reactions with the alkaline solution [101]. The capacity of highly crystalline materials for ion exchange and chemical interactions with an activator may be limited and can hinder the dissolution of essential components needed for the activation process [102]. The poor reactivity of mine tailings is a significant challenge in their utilization for alkali-activated materials. Poorly reactive mine tailings may contribute less to the strength and durability of alkali-activated materials and can limit their usefulness as a primary component in construction. The slow reactivity of highly crystalline mine tailings can result in slower activation kinetics and require longer curing times or additional processing to achieve the desired properties [103]. Additional processing steps like mechanical activation or thermal treatment may be necessary to enhance

the reactivity of mine tailings, adding complexity and cost to the recycling process. One way to enhance the reactivity of poorly reactive mine tailings is by combining them with a reactive co-binder, such as metakaolin or blast furnace slag, in an alkali activation process. This approach enhances the strengths of both materials to create a more effective and sustainable material [104]. However, the reactivity of mine tailings can be enhanced through various treatment methods aimed at modifying the physical and chemical properties of the tailings to make them more suitable for the alkali activation process. Finally, the decision to use mine tailings as a binder or inert filler should be made after carefully assessing their reactivity. This reactivity, in turn, is influenced by the mineralogical composition of the tailings and how they respond to various treatment processes.

3.2. Mine Tailings as a Filler Material in Alkali Activation

Using mine tailings as a filler material in alkali activation is a sustainable approach to repurposing mining waste. Mine tailings with low levels of reactivity can find a valuable role as inert fillers in alkali activation when combined with an appropriate co-binder material [105]. This approach helps us use tailings that might otherwise have limited levels of reactivity. Different studies demonstrate the potential of alkali activation as a stabilizing method for a range of mine tailings, including those from base metal, coal, uranium, and potash mining sites, and the crucial role of metakaolin as a co-binder [106–108]. Alkali activation, as a versatile process, not only has a great capacity to immobilize hazardous elements but also results in a final matrix with a robust mechanical performance, making alkali activation a sustainable solution for repurposing mine tailings. Analyzing the geochemistry of Kaltails tailings produced under different conditions is crucial before utilizing them in alkali-activated materials, which provides critical insights into the chemical composition, mineralogy, and potential reactivity of the tailings [109]. The material composition, rich in Si (silicon), Al (aluminum), Mg (magnesium), Fe (iron), Na (sodium), and SO₃ (sulfate), suggests a potentially reactive mixture when combined with fly ash or blast furnace slag, demonstrates excellent mechanical properties, and good levels of durability and permeability. Notably, these positive outcomes were achieved when the mixture had a low proportion of tailings (less than 70 wt%), indicating that even with a relatively low proportion of tailings, they could contribute to the desirable properties of the final material significantly, demonstrating the potential for effectively utilizing mine tailings as a valuable component in construction materials [110].

Studies provide valuable insights into the alkali activation of copper mine tailings, which consist of minerals like quartz, albite, potassium aluminum silicate, and gypsum, contributing to the reactivity of the tailings. Sodium hydroxide (NaOH) was employed as the activator to initiate the polycondensation reactions necessary for forming a 3D structure in a material [111,112]. Studies have also highlighted the essential role of a co-binder in achieving good mechanical properties and levels of durability in the final material, suggesting that the inherent reactivity of copper mine tailings alone may not be sufficient to achieve the desired properties [113]. Adding fly ash to the mixture further enhanced the final strength of the alkali-activated copper mine tailings. The successful alkali activation of copper mine tailings and the essential role of co-binders underscore the potential for repurposing mining waste in sustainable construction materials [114]. Moreover, optimizing the curing conditions can substantially impact the mechanical properties of alkali-activated materials. Specifically, a study demonstrated that better mechanical properties were achieved by carefully controlling the curing conditions. This involved either controlling the pressure or using an elevated curing temperature of 90 °C [115].

The composition of the mine tailings, including dolomite, kaolinite calcite, and quartz, from the vanadium mining site in China provides insight into the potential reactivity and properties of these materials. The tailings were used as a raw material in alkali activation, with metakaolin as a co-binder and sodium silicate as an activator [116].

Another study used metakaolin, a thermally activated form of kaolinite clay, as a co-binder for molybdenum mine tailings, with the potential for the use of mining waste. The

molybdenum mining site was rich in minerals like quartz and calcite and phases containing calcium, aluminum, and iron [117]. It was found that with a greater content of metakaolin, there was a greater amount of tetrahedral silicon (Si) coordination in the geopolymer gel, and the greater metakaolin content resulted in the final material having better mechanical properties [118]. Furthermore, gold mine tailings that were rich in dolomite, quartz, sulfur, and mullite were studied. The study highlighted the necessity of a suitable co-binder, such as blast furnace slag or metakaolin, for the alkali activation process and suggested that the gold mine tailings alone may not have been reactive enough to achieve the desired hardening. A matrix suitable for construction material was generated by incorporating a higher co-binder content. However, employing a high concentration of NaOH (15 M) led to a notable reduction in the workability of the resulting paste, potentially exerting a substantial influence on the properties of the final material [119].

The use of alkali activation in paste backfill technology represents an intriguing avenue in sustainable construction practices. An inverse relationship is observed when employing alkali-activated blast furnace slag in conjunction with gold mine tailings containing quartz, albite, mica, sanidine, and microcline for the production of paste backfill material; as the compressive strength of the final matrix increases, the workability of the mixture decreases [120]. The superior strength exhibited by the matrix, compared to Portland-cement-based paste, under optimal curing conditions and with an ideal concentration of the alkali activator (a blend of NaOH and Na₂SiO₃), affirms the appropriateness of alkali-activated slag as a co-binder in paste backfill technology [121]. Alkali-activated fly ash can serve as a co-binder for sulfidic-rich mine waste rocks, enabling the production of paste backfill materials or construction materials. Utilizing sulfidic waste rock as the aggregate significantly reduces the acid generation potential of the waste in landfills, resulting in the production of environmentally acceptable materials. This stands as one of the foremost advantages of employing alkali activation in paste backfill technology, as opposed to ordinary Portland cement (OPC) [122].

Mine tailings, which may have a limited reactivity on their own, can contribute to the final material when used as an inert filler when suitable co-binder materials, like metakaolin or blast furnace slag, are chosen. Each type of mine tailing requires a meticulous study of mix design due to the influence of mineralogy, chemical composition, and physical properties on co-binder materials, alkali activators, and process conditions [123]. However, the accessibility of a co-binder is equally crucial, as the mining site may not always be in close proximity to the industry or manufacturing facility that produces a compatible co-binder. The summarized results of relevant studies are shown in Table 2.

Table 2. Summary of studies using various mine tailings as filler materials in alkali activation.

Mine Tailings	Procedure Parameters	Main Elements	Mineralogy	Final Properties	Ref.
Metal, coal, uranium, and potash tailings	Liquid toxic waste mixed with a geopolymer precursor; curing at 60 °C	-	-	High immobilization of heavy metals; high mechanical performance	[106–108]
Kaltails tailings	Fly ash as a co-binder	Si, Fe, Al, Ca, Mg, Na, and SO ₃	-	Maximum mine tailing content of 70 wt%; stronger hardpan achieved with greater fly ash content	[109,110]
Copper tailings	Fly ash as a co-binder; curing at 90 °C; pressure used in preparation stage	-	Quartz, albite, potassium aluminum silicate, and gypsum	Improved mechanical strength with higher co-binder content and elevated curing temperature	[111–115]

Table 2. Cont.

Mine Tailings	Procedure Parameters	Main Elements	Mineralogy	Final Properties	Ref.
Molybdenum tailings	Metakaolin as a co-binder; curing at room temperature	-	Calcite, andradite, quartz, dolomite, and calcium aluminum silicate	The improved strength of the final material with metakaolin	[116–118]
Gold tailings	Blast furnace slag and metakaolin as co-binders; curing at room temperature	-	Dolomite, quartz, chlinoclore, muscovite, albite, and gypsum	Metakaolin used for adjusting the scarce Al content in the mixture; the effect of co-binder content on the mechanical properties of the final material	[119]
Gold tailings	Slag, gypsum, cement, lime, and silica fume as co-binders	-	Quartz, albite, mica, sanidine, and microcline	Appropriate material to utilize for paste backfill technology	[120,121]
Sulfidic mine waste rock	Fly ash as a co-binder	-	Chlorite, quartz, illite, and pyrite	Suitable to utilize sulfidic mining waste rock as aggregate in alkali activation	[122]

4. Pre-Treatment Methods

Addressing the poor reactivity of mine tailings is a crucial aspect of their utilization in alkali activation technology. Due to the observed low level of reactivity of mine tailings in alkaline conditions, various pre-treatment methods have been explored to augment the reactivity of distinct minerals. Mechanical activation, heat treatment or calcination, and alkaline fusion have been the subject of extensive research in this context. This review delves into a discussion of how each method impacts the reactivity of various minerals.

4.1. Mechanical Activation

Mechanical activation is a crucial pre-treatment step in maximizing the potential of mine tailings for use in alkali activation technology. The primary goal of mechanical activation is to enhance the reactivity of specific components within the mine tailings. This is achieved by subjecting the material to grinding or milling processes, including reducing the particle size, increasing the surface area, and disrupting crystalline structures [124]. The increased reactivity observed after milling is attributed to the higher amorphous content of the reactive elements. As the particle size of the mine tailings is reduced through milling, the total surface area of the material increases significantly since smaller particles have a more exposed surface area relative to their volume. This increased surface area means that a larger proportion of the material is now available for chemical reactions, allowing for a greater number of reactive sites to participate in the formation of the 3D structure [125]. The larger surface area facilitates faster reaction kinetics, meaning that chemical reactions can occur more quickly, leading to a more efficient alkali activation process [126].

A study focused on investigating mechanical treatments with the aim of enhancing the ultimate properties of alkali-activated mine tailings originating from a vanadium mining site that were primarily composed of quartz, feldspar, diopside, mullite, and hematite. After a 60 min grinding process, the particles exhibited a more uniform shape, and the average particle size was reduced from 31 to 2 μm , resulting in a higher mechanical strength in the final alkali-activated material [127]. Furthermore, the grinding process led to the increased solubility of silicon (Si) and aluminum (Al) in the material [128]. The ultimate alkali-activated materials were created by blending mine tailings, fly ash, and solid sodium silicate powder. This dry mixture was subsequently combined with water, exhibiting superior thermal resistance properties compared to those of composites made with Portland cement [127,129].

Copper mine tailings that were rich in quartz, albite, dolomite, and chlorite were studied. After grinding copper mine tailings for 3 h, a remarkable increase in solubility was observed. Specifically, there was a 93% higher solubility of aluminum (Al) and a 23% higher solubility of silicon (Si) compared to a mine tailing material that was not ground [130].

Antigorite ($Mg_3Si_2O_5(OH)_4$)-rich mining waste was also mechanically activated. The tailings were milled with a planetary mill (0.5–10 min). According to that study, the process of dehydroxylation was evidently linked to the generation of a greater amount of amorphous material during the milling process. Furthermore, there was a notable increase in the solubility of silicon [131].

Phyllite-rich material was studied, and its cementitious properties were demonstrated following the milling process. Phyllite is a type of metamorphic rock that forms from the metamorphism of shale or mudstone, belonging to the category of foliated metamorphic rocks, which means it has a layered or banded appearance due to the alignment of minerals under heat and pressure. The decrease in muscovite and chamosite content was noticeably evident, whereas the quantity of quartz remained unchanged, and the amorphous content increased by mechanical activation [132]. The summarized results of relevant studies are shown in Table 3.

Table 3. Summary of studies regarding mechanically activated mine tailings.

Mine Tailings	Procedure Parameters	Mineralogy	Mineralogical Changes	Ref.
Vanadium tailings	60 min grinding; 10:1 weight ratio of grinding ball to powder	Quartz, feldspar, diopside, mullite, and hematite	Decreased amount of crystalline quartz; higher mechanical strength of alkali-activated material obtained with higher leaching of Al and Si and higher amorphous content	[127]
Copper tailings	1–4 h grinding; 10:1 weight ratio of grinding ball to powder	Quartz, dolomite, chlorite, and albite	Decreased content of albite (lower crystalline silica content)	[130]
Antigorite waste	600 s grinding; 6:1 weight ratio of grinding ball to powder	Mg and Si minerals	Cementitious properties obtained in milled mine tailings	[131]
Phyllite waste	9–15 min grinding	Clay, quartz, and albite	Reduction in chamosite and muscovite; decreased albite content	[132]

4.2. Heat Treatment

Conducting a preliminary heat treatment prior to alkali activation has displayed the potential to augment the reactivity of mine tailings [133]. The heat treatment of mine tailings is a process aimed at modifying their chemical and physical properties by subjecting them to high temperatures to induce changes in their mineralogy and reactivity, improving their suitability for various applications. One specific effect of this treatment is the removal or alteration of hydroxyl groups, which are oxygen and hydrogen atom pairs (-OH) found in minerals [134]. The specific temperature range used in heat treatments can vary depending on the desired outcomes and the composition of the tailings. The high temperatures applied during heat treatment can lead to the removal of hydroxyl groups from minerals containing hydroxyl groups, such as clays and certain silicates present in the tailings, and transform them into more stable phases with altered properties for the formation of a 3D structure [135]. Moreover, elevating the temperature can facilitate the dissolution of aluminum and silicon units from the original material, heightening its reactivity in alkaline conditions. When mine tailings are subjected to high temperatures during heat treatment, the intense thermal energy causes the minerals to change, leading to the generation of amorphous phases. The higher amorphous content means that a larger portion of the material is now in a highly reactive state, crucial for subsequent processing steps, like alkali activation [136].

A pioneering investigation used a thermal pre-treatment before alkali activation to enhance the reactivity of tungsten mine tailings, which were notably abundant in quartz and muscovite. The study revealed a substantial thermal resistance in quartz,

whereas a portion of the muscovite (approximately 12%) remained unchanged even after exposure to temperatures exceeding 950 °C [137]. Subsequent research indicated that boron mine tailings, which included Ca and Mg minerals like colemanite and hydroboracite, transformed into an amorphous state at 600 °C [138]. Illite, a mineral with properties akin to those of muscovite, underwent decomposition at 800 °C, while albite decomposed only at temperatures above 900 °C [139,140].

Another study delved into the utilization of heat-treated phosphate mine tailings as a raw material in alkali activation in conjunction with fly ash and metakaolin. During alkali activation, dolomite and calcite underwent a reduction process, whereas other phases, like quartz, fluorapatite, and mullite, remained unaffected [141]. In the case of kaolinite tailings, calcination at 750 °C emerged as the most efficient approach to enhance their reactivity. This is attributed to the probable transformation of kaolinite into metakaolin during decomposition [142]. It is crucial to note that optimizing the calcination temperature is paramount, as metakaolin continues to react and produces crystalline and insoluble mullite. This transformation becomes noticeable at temperatures surpassing 800 °C [143]. Moreover, copper tailings have displayed heightened levels of reactivity following calcination at 600 °C, coinciding with the observed decomposition of crystalline chloride [144]. The summarized results of relevant studies are shown in Table 4.

Table 4. Summary of studies regarding heat-treated mine tailings.

Mine Tailings	Main Minerals	Calcination Temperatures	Mineralogy Changes	Other Comments	Ref.
Tungsten tailings	Muscovite and quartz	950 °C	High thermal resistance for muscovite	Increased amount of amorphous phase; thermal behavior similar to that of phyllosilicate minerals	[137]
Boron tailings	Colemanite ($\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 5\text{H}_2\text{O}$), hydroboracite ($\text{CaMgB}_6\text{O}_8(\text{OH})_6 \cdot 3\text{H}_2\text{O}$), quartz, illite, and calcite	600, 700, and 800 °C	Colemanite and hydroboracite turned into amorphous phase at 600 °C; illite and calcite decomposed at 800 °C	Illite had similar properties to muscovite	[138]
Phosphate tailings	Quartz, calcite, fluorapatite, dolomite, mullite, and feldspar	750 °C (2 h)	Quartz, fluorapatite, and mullite remained constant; dolomite and calcite content was reduced; feldspar content was eliminated	High mechanical strength achieved with 50 wt% phosphate tailing in the mixture	[141]
Kaolinite tailings	Muscovite, kaolinite, and quartz	750 °C	Kaolinite turned into amorphous metakaolin	Possible recrystallization of amorphous phase beyond optimum temperature	[142]
Copper tailings	Quartz, albite, chlorite, and dolomite	400–600 °C	Crystalline chlorite was dissolved	-	[144]

4.3. Alkaline Fusion

Alkaline fusion is a chemical process that involves heating a material, typically in the presence of an alkaline substance like sodium hydroxide (NaOH) or potassium hydroxide (KOH), to create a fusion or reaction. This process is used to alter the composition and properties of the material and increase the reactivity of the material prior to alkali activation [145]. In the context of mine tailings, alkaline fusion refers to subjecting the tailings to high temperatures in the presence of an alkaline substance. The high temperatures and alkaline environment cause chemical reactions within the tailings, leading to the transformation of the minerals into different phases or forms. The process involves elevating the temperature beyond the melting point of the alkali source present in the mixture. Following this heat treatment, the processed material is subjected to alkali activation using an alkaline solution. Alkaline fusion can facilitate the removal of impurities or unwanted components from the tailings, making them more suitable for specific applications [146].

A study investigated alkaline fusion in conjunction with poorly reactive volcanic ash. This process resulted in a greater quantity of soluble aluminosilicates due to the conversion of minerals like muscovite, anorthoclase, and diopside. Consequently, this led to an enhancement in the reactivity of the ash [147].

Alkaline fusion has been explored as a method for treating gold mine tailings. In this process, an Al_2O_3 additive was blended with the tailings at different concentrations, and NaOH pellets were introduced to the mixture. The fusion process was carried out at $550\text{ }^\circ\text{C}$ for 1 h, with the temperature increasing at a rate of $10\text{ }^\circ\text{C}$ per minute. Following the heating process, the mixture was combined with Na_2SiO_3 . It was observed that the primary factor influencing the reactivity was the content of Al_2O_3 rather than the curing temperature [52].

A study on alkaline fusion with granite waste was also conducted, and it was found that the crucial factor influencing the reactivity of the material was the quantity of alkaline reagent applied [148]. Moreover, when alkaline fusion was employed with phosphate tailings, notable changes were observed [149]. This included the decomposition of illite, palygorskite, and dolomite phases alongside an augmentation in the content of Na-rich crystalline phases [150].

5. Conclusions

Mine tailings constitute the largest volume of solid waste generated by the mining industry. Unfortunately, due to their limited economic value, a significant portion of these tailings are typically deposited in controlled landfills submerged underwater. The land-filling of mine tailings has not always been viewed as a significant problem. However, their environmental impacts, especially incidents like tailing dam failures leading to tailing draining or flooding, have resulted in severe consequences, including a loss of life, leading to the issue gaining critical attention. Consequently, stringent legislative regulations have compelled the mining industry to explore alternative methods of disposal. The possibility of employing mine tailings as a primary material in alkali activation has garnered significant attention from researchers. Among the crucial factors for examination, the mineral composition of mine tailings takes precedence. Predominantly, these tailings exhibit low levels of reactivity under alkaline conditions based on their mineralogy. Therefore, using them as a raw material in alkali activation proves to be challenging due to this inherent low level of reactivity. Mine tailings can be effectively employed as an inert filler in alkali activation technology, especially when combined with a compatible co-binder, like metakaolin, fly ash, or blast furnace slag. Factors such as curing conditions, the duration of curing, the type and concentration of the alkali activator, and the choice of co-binder materials all exert pivotal influences on this process. Sustainable high-performance building materials can be created that leverage waste materials for environmental and economic benefits and that can be tailored to specific requirements by adjusting the mix design and using different types of aluminosilicate precursors. An alternative approach involves enhancing the reactivity of the initial material through methods like thermal treatment, mechanical activation, or alkaline fusion before subjecting it to alkali activation. Alkali-activated mine tailings hold potential applications as construction materials and as recyclable paste backfill materials. Furthermore, this method can serve as a stabilization approach before landfilling, particularly for managing hazardous mine tailings. Finally, future studies on mine tailing alkali-activated materials could focus on optimizing activation processes to enhance the mechanical and durability properties of mine tailings. Moreover, performing life cycle assessment (LCA) analyses to develop sustainable and efficient activation methods by understanding the long-term environmental impact and stability of these materials should be considered.

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