Utilization of Mine Tailings Activated with NaOH and KOH for Alkali-Activated Cement: a Strategy for Waste Minimization

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Abstract

This study investigates the feasibility of using mining tailings as a precursor material for alkali-activated cement to address both the mitigation of environmental pollution from the disposal of mining industrial waste and the reduction of CO2 emissions associated with Portland cement production. X-ray fluorescence analyses conducted on mine tailings revealed a chemical composition suitable for the generation of Alkali-activated materials (AAMs). X-ray diffraction analysis showed the presence of crystalline phases of calcite and quartz in the tailings in their natural state. Experiments were carried out to study the effect of two activators, NaOH and KOH, at concentrations of 2, 4, 6, 8, and 10M, mixed with the tailings sample. It was observed that when testing a concentration of 10M of both activators, the characteristic peaks of calcite disappeared, giving rise to portlandite. Additionally, the formation of sodium and potassium carbonates was evidenced, depending on the activator. To evaluate the activation process, tests were conducted with different stirring times, results indicated that 15 minutes of stirring were comparable to 24 hours of agitation. Furthermore, a compressive strength analysis was performed on specimens prepared with a concentration of 10M of both activators, cured at 3, 14, and 28 days. Compressive strength tests yielded results of 16.4 MPa with NaOH and 14.6 MPa with KOH after 28 days of curing, and SEM-EDS analysis indicated geopolymerization processes in the materials.

Keywords: alkaline activation; alkali cements; compressive strength; mine tailings.

Introduction

Mining is a global industry that generates large volumes of waste, known as tailings, which are typically stored in tailings dams and ponds near extraction sites, where they remain for extended periods, even after mining operations have ceased (Shengo, 2021). The storage of tailings poses a significant environmental risk worldwide. Due to their fine particle size, tailings often generate airborne emissions (Bortnikova et al., 2022; Kasongo et al., 2024), presenting serious environmental challenges, including contamination of air, soil, and water (Damoah et al., 2022). Additionally, they may contain heavy metals and hazardous reactive compounds. Failures in tailings dams are among the leading causes of mining-related environmental disasters, highlighting the urgent need for alternative waste management strategies, such as the reuse and recycling of these residues (Hernández-Ramos et al., 2024; Lee et al., 2024).

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One viable approach to tailings reuse is their incorporation into cementitious binders, such as ordinary Portland cement (OPC), to produce cemented paste backfill (Ercikdi et al., 2009; Li et al., 2019). Their use has also been proposed as an additive or partial replacement in blended Portland cements (Gou et al., 2019). The cement industry plays a crucial role in global economic development and infrastructure; however, it faces challenges such as rising energy costs and the imperative to reduce greenhouse gas emissions (Barcelos et al., 2020; Csavina et al., 2012). In this context, the use of mining waste in civil engineering and construction materials is emerging as an environmentally friendly and cost-effective solution (Lin Chen et al., 2024). This approach includes aggregate substitution, enhancement of cement properties, partial clinker replacement, and the production of alkali-activated cements (Torres-Carrasco et al., 2017).

AAMs are an emerging class of alternative binders to OPC, in which a solid aluminosilicate precursor reacts with an alkaline activator to form a hardened alkali aluminosilicate binder with properties comparable to OPC (Yin et al., 2024). AAMs include alkali-activated cements, as well as conventional two-part geopolymers where the activator is mixed with water and then mixed with the material, and one-part geopolymers, where only water is added, similar to process used with OPC (Adesina, 2025; Segura et al., 2022; Zareechian et al., 2023). Extensive research has been conducted on AAMs, and they are considered a promising alternative to conventional cement due to their lower environmental impact (Cong et al., 2021; Singh et al., 2020).

Alkali activation, or geopolymerization, is a process that converts aluminosilicate sources into durable polymeric structures using alkaline solutions (Kriven et al., 2024). This results in materials with high compressive strength, durability, and the ability to immobilize toxic metals, making them suitable for construction applications (Arel et al., 2019; Sambucci et al., 2021). While extensive research has been conducted on the geopolymerization of industrial by-products such as slags and fly ash (Liang Chen et al., 2016), the alkali activation of gold and silver tailings remains a relatively unexplored field with significant potential.

Recent research consistently demonstrates that mine tailings–whether derived from copper, lead–zinc, nickel, manganese, multimetallic deposits, sulfidic ores, or other sources–hold significant potential as total or partial precursors in the production of geopolymers, the Table 1 summarising the main findings of other authors. When subjected to appropriate alkaline activation and with careful control of the Si/Al ratio, these materials can achieve competitive mechanical strengths, often exceeding 25–35 MPa, while also improving durability against chemical attack and, in many cases, effectively immobilizing heavy metals present in the waste. The reviewed studies highlight viable applications ranging from structural components and prefabricated elements to 3D printing, road base stabilization, and the environmental rehabilitation of mining sites.

Despite these promising results, several recurring challenges emerge. The chemical and mineralogical variability of tailings from different sources complicates the standardization of mix designs. Certain types, particularly sulfidic and iron-rich tailings, exhibit low initial reactivity, necessitating more intensive thermal or chemical activation. The presence of contaminants such as sulfates, arsenic, and other heavy metals can interfere with geopolymerization or cause environmental risks if not adequately encapsulated. Moreover, most investigations remain at the laboratory scale, with limited pilot or industrial-scale validation, and the absence of specific regulatory frameworks for the use of mine tailings in construction materials continues to hinder broader adoption.

In line with the identified needs, this research directly addresses the search for a precharacterization of the design minerals for their use in the production of geopolymers as a cementing material to generate a viable alternative to Portland cement. This involves the application of analytical techniques such as X-ray diffraction (XRD), X-ray fluorescence XRF, and scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS) to determine the mineralogical composition, chemical reactivity, and determine their viability for the synthesis of geopolymers,

evaluating alkaline activation with sodium hydroxide and potassium hydroxide at different molar concentrations of each activator. Pastes of the samples were prepared at a concentration of 10 M, followed by thermal curing at 80 °C for 24 hours. Subsequent curing was carried out at room temperature (22 °C) for 3, 14 and 28 days to determine the evolution of their compressive strength properties and reaction products.

Table 1
Geopolymers Using Mine Tailings

Type of Mine Tailings	Key Technical Findings	Limitations / Recommendations	Reference
Multimetallic tailings (3D printing)	Good workability, compressive strength >25 MPa, suitable for additive manufacturing	Requires particle size control and tailored alkaline activation	Morales Aranibar et al., 2025
Copper tailings	High mechanical strength, good densification, suitable for road base layers	Sulfate removal and optimized alkaline activation needed	Faheem et al., 2024
Sulfidic coal tailings	Partial replacement of metakaolin feasible, effective heavy metal encapsulation	Thermal activation improves reactivity	Mokhtari et al., 2025
Peruvian tailings (Arequipa)	Optimized Si/Al ratio enhances strength and durability	Requires detailed mineralogical characterization due to chemical variability	Palma et al., 2024
Tailings as aggregate (Italy)	Improved physical properties in fly ash-based geopolymers, good dimensional stability	Not reactive precursors; recommended as inert aggregate	Capasso et al., 2019
Tailings blended with fly ash	Enhanced strength and cohesion when combined with fly ash	Requires proportion control to avoid brittleness	Zhang et al., 2011
Multimetallic tailings (Tunisia)	Good durability and low metal leaching	Pre-inerting needed to prevent acid reactions	Ben Amor et al., 2022
Small-scale mining tailings (Mexico)	High strength (>35 MPa), low Pb and Zn leaching, good durability	Controlled alkaline activation and residual metal analysis recommended	Rincón et al., 2023
Sulfidic tailings (Portugal/ Finland)	Function as fine aggregate, chemically stable	Not active precursors; recommended to blend with metakaolin or fly ash	Paiva et al., 2019
Finnish tailings (review)	Potential as active precursor, contributes to sustainable binder development	Requires chemical and thermal activation to improve reactivity	Yliniemi et al., 2020
Arsenic-rich tailings	Effective arsenic encapsulation, significant leaching reduction	pH control and activator selection critical to prevent secondary release	Zhang et al., 2021
Lead-zinc tailings	High mechanical strength, favorable microstructure	Requires adjustment of liquid-to-solid ratio and alkaline activation	Liu et al., 2022
Nickel tailings	Viable as partial precursor, improved strength and cohesion	Blending with metakaolin recommended to enhance performance	Park et al., 2023
Manganese tailings	Good rheology and early strength, suitable for non-structural applications	Requires control of metal content and thermal activation	Huang et al., 2024.
Zinc tailings	Enhanced strength and durability when blended with slag	Proportion and activator control needed to prevent alkali-silica expansion	Zhao et al., 2020.

Materials and test methods

Raw Materials

The mine tailings (MT) used in this study were collected from a gold and silver mining operation located in Peña de Bernal, Querétaro, México. The as-received material presented a partially moist powder state with presence of agglomerated lumps. To ensure homogeneity and reliability of subsequent analyses, the MT was dried at 110°C until a constant weight was achieved. The dried material was then manually quartered to obtain representative samples and sieved through a 0.25 mm mesh to remove oversized particles. This preparation process allowed the material to be conditioned for subsequent physical, chemical, and mineralogical characterization, ensuring consistency in the evaluation of its potential use for alkali-activated cement.

Fig. 1a shows the tailings in recovery conditions, an irregular granulometry can be seen, in Fig. 1b the tailings can be seen without moisture and sieved using a No. 60 sieve used to prepare the specimens.

Fig. 1

a Tailings in recovery conditions, **b** tailings dried and screened by sieve No. 60 (0.25mm).

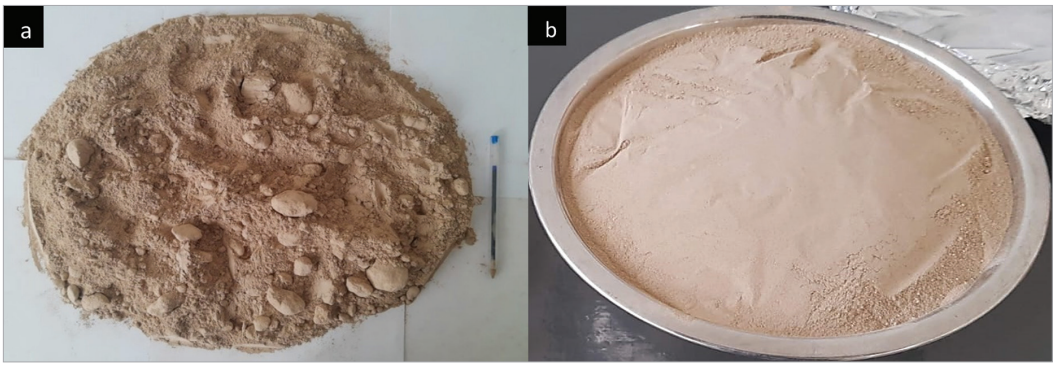
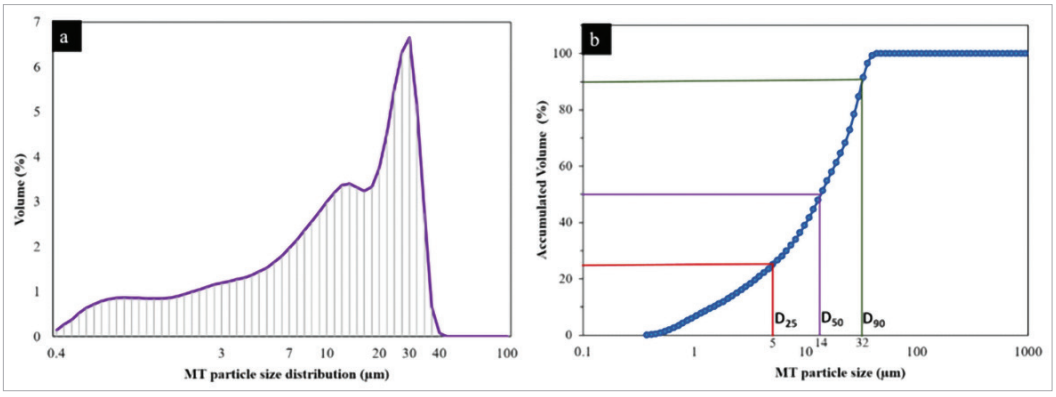


Fig. 2a shows the MT particle size distribution as a bimodal distribution curve where the first curvature is between 10 and 15 µm, and the second between 20 and 40 µm. It is also noted that all the material features sizes below 50 µm. From the cumulative distribution shown in Fig. 2b, the D_{25}, D_{50}, and D_{90} were determined, which correspond to 5, 14, and 32 µm, respectively.

Fig. 2

a MT particle size distribution, **b** particle size distribution data D_{25}, D_{50}, and D_{90}.



The chemical characterization of the MT by XRF revealed that the main components are silicon and calcium, with low aluminum content (3.27 %) <5%. Given their high SiO_2 (55.3 %) and CaO (35.0 %) concentration (>70%), it is expected that alkali activation will generate a gel similar to C-S-H, typical of conventional cement. The incorporation of aluminum could favor the formation of C-A-S-H gel, improving its properties (Cristelo et al., 2020).

SEM analysis of MT reveals that the particles display highly heterogeneous morphology, with irregular shapes and a broad range of sizes, ranging from approximately 10 µm to nanoscale fine

powders, Fig. 3a. The larger particles, primarily composed of silicon, correspond to quartz, while rounded grains and aggregates contain calcium, associated with the calcite phase, as shown in the chemical mapping Fig. 3b. Energy-dispersive X-ray spectroscopy (EDS) analysis in Fig. 3c confirmed the presence of silicon in point 1. It has been documented that tectosilicates, such as quartz, typically exhibit irregular and angular morphologies. Additionally, small rounded and porous particles were observed in Fig. 3a, point 2, which, according to EDS analysis (Fig. 3d), contain a high calcium content, suggesting a possible association with carbonate phases or other reactive mineral phases. These morphological characteristics, particle size distribution, and chemical composition may influence the reactivity of the material (Karunadasa et al., 2019; Ren et al., 2021; Yao et al., 2019).

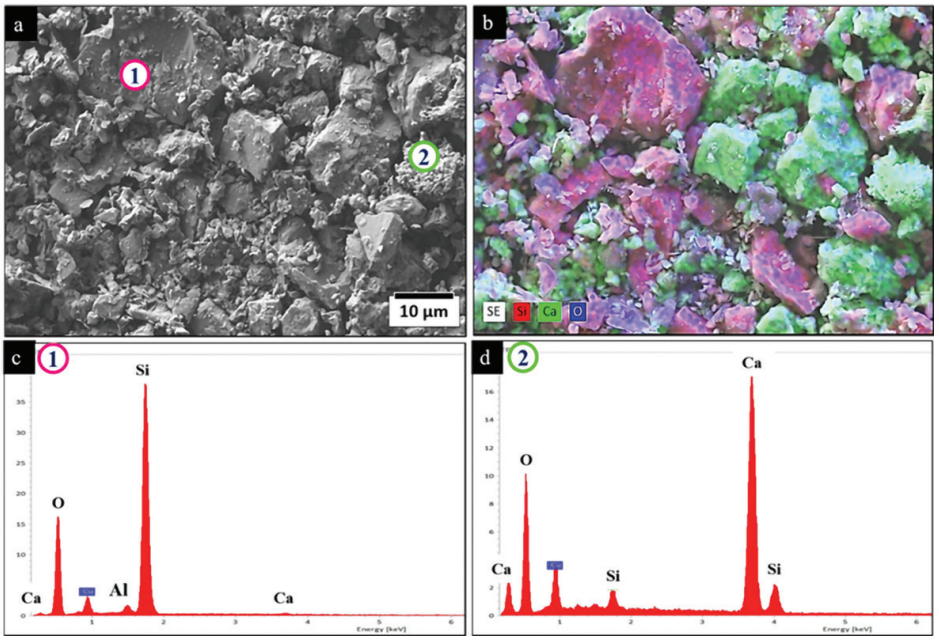


Fig. 3

SEM images of **a** MT, **b** chemical mapping of MT, **c** SEM-EDS point 1, and **d** SEM-EDS point 2.

Activators

Alkali activation was evaluated using two solutions: NaOH was purchased from Meyer. It comes in flake form and has a purity of 95%, molecular weight: 40 g/mol, boiling point: 1388-1390 °C, melting point: 318 °C, density: 2.13 g/cm^3 at 20 °C. KOH was purchased from Meyer. It comes in pellet form and has a purity of 88%, molecular weight: 56.11 g/mol, boiling point: 1320 °C, melting point: 360 °C, density: 2.04 g/cm^3 (20 °C).

Characterization of the raw material and alkali-activated material

The MT were characterized by Particle Size Distribution (PSD) analysis with a Beckman Coulter LS 100Q equipment (5 g of material in dry medium) and chemical composition was determined using X-ray fluorescence spectrometry (XRF) with the Bruker D8 Tiger team. Crystalline phase identification was made by X-ray diffraction (XRD) with a Bruker D8 Advance equipment, with Cu-Kα radiation and Ni filter, data were recorded in a range 2θ of 10° to 80° with a step size of 0.02° and 0.6 s/step. The crystalline phases in samples were identified using the X'Pert HighScore Plus 2.2™ computer software database. A scanning electron microscope JEOL JSM 6400 was used for morphological characterization, and an energy-dispersive X-ray spectroscopy (EDS) microanalysis was conducted to identify the elements in samples.

Alkaline activation with MT

NaOH and KOH solutions were prepared at concentrations of 2, 4, 6, 8, and 10M, mixed with the MT with a liquid/solid ratio of 2.22, and stirred at 350 rpm for 24 hours at room temperature. After filtration and drying, the most suitable concentration of the material was evaluated using XRD. The stirring time (15 min, 1 h, and 24 h) was optimized, and the activated material was analyzed.

Preparation of alkali-activated specimens

The standards followed for the preparation and determination of cube strength were ASTM C109 and NMX-C-061-ONNCCE. Sample preparation involved a 10 M alkaline solution stirred at 350 rpm for 15 minutes. The tailings were mixed with the solution at a liquid/solid ratio of 0.25 in a planetary mixer for 15 minutes, and 50 mm cubes were molded. These cubes were thermally cured at 80 °C in a humid environment (80%) for 24 hours (Majdoubi et al., 2021). They were subsequently demolded and subjected to moist curing at room temperature for 3, 14, and 28 days. After curing, the cubes were evaluated for compressive strength. Fragments of the samples were subsequently analyzed by SEM-EDS to assess the resulting microstructure. Table 2 shows the dimensions and weights of the specimens before the mechanical resistance test as suggested by the ASTM C109 standard. In the last column on the right side, it was decided to include the load in kg-force that each specimen reached after the mechanical resistance test. It can be seen that the weight or density of each specimen is not directly related to the load supported and that the resistance reached can be mainly attributed to the geopolymerization process.

Table 2

Dimensions and weights of specimens before mechanical strength testing.

Activator and molarity	Curing time (days)	Nomenclature	Long (mm)	Broad (mm)	Unit weight (g/cm^3)	Compressive strength (MPa)	Average (MPa)
NaOH 10M	28	NaOH 1	50	50	1.99	16.1	16.4
		NaOH 2	51	50	1.9	16.8	
		NaOH 3	50	50	1.97	16.4	
	14	NaOH 4	50	50	1.94	15.5	15.3
		NaOH 5	50	50	1.98	15.4	
		NaOH 6	51	50	1.91	15.2	
	3	NaOH 7	51	50	2.01	12.5	12.7
		NaOH 8	51	50	2.01	12.6	
		NaOH 9	50	50	2.01	12.9	
KOH 10M	28	KOH 1	51	50	1.95	15.1	14.6
		KOH 2	50	50	1.99	14.1	
		KOH 3	50	50	1.97	14.5	
	14	KOH 4	50	50	1.99	13.2	13.4
		KOH 5	51	50	1.94	12.8	
		KOH 6	51	50	1.94	14.2	
	3	KOH 7	51	50	1.94	10.9	10.5
		KOH 8	51	50	1.95	10.0	
		KOH 9	50	50	1.99	10.6	

Characterization of the alkali-activated material

Crystalline structure of alkali-activated MT at different concentrations

Fig. 4 shows X-ray diffraction (XRD) analysis, it reveals high crystallinity in the MT, with prominent peaks of quartz SiO_2 (PDF 03-065-0466), and calcite $Ca(CO_3)$ (PDF 01-086-2334), corroborating the XRF and EDS results, indicating higher purity compared to (Rao et al., 2015). The mineralogical analysis of the alkali-activated MT showed that the alkaline dissolution treatment and molar concentration of each activator significantly affect the structure of the MT. Fig. 4 presents the XRD patterns of MT activated with NaOH at concentrations of 2M, 4M, 6M, 8M, and 10M. It can be observed that as the activator concentration increases, the crystalline phases of calcite decrease. At concentrations of 6M, 8M, and 10M, peaks corresponding to the portlandite phase appear $Ca(OH)_2$ (PDF 01-078-0315). At 8M and 10M, the calcite phase disappears and sodium carbonate Na_2CO_3 (PDF 01-077-2082) and potassium carbonate K2CO3 $1.5H_2O$ (PDF 00-011-0655), phases are generated. The formation of the portlandite phase occurs due to the release of Ca^{2+} ions from calcite and their interaction with OH^- ions from hydroxides (sodium or potassium) and the mixing water. Meanwhile, the formation of carbonates takes place because the activator releases metal ions when in contact with water, such ions can be either sodium (Na^+) or potassium (K^+), which carry a positive charge. To stabilize, these ions bond with free carbonate ions (CO_3^{2-}) from calcite (which previously released Ca^{2+} ions).

Fig. 5 shows the XRD patterns of MT activated with KOH at concentrations of 2M, 4M, 6M, 8M, and 10M. As the activator concentration increases, the crystalline phases of calcite decrease. From 4M onwards, potassium carbonates are formed, and at 8M, portlandite appears due to the interaction between OH^- ions and calcium released from the MT. The quartz phase did not exhibit significant structural changes with any activator at any molar concentration due to the high crystallinity of its structure (Ringdalen, 2015), quartz is less reactive than other aluminosilicate materials, however, some authors claim that the MT particles partially react, explaining their reactivity in activated systems (Liu et al., 2024). Despite this,

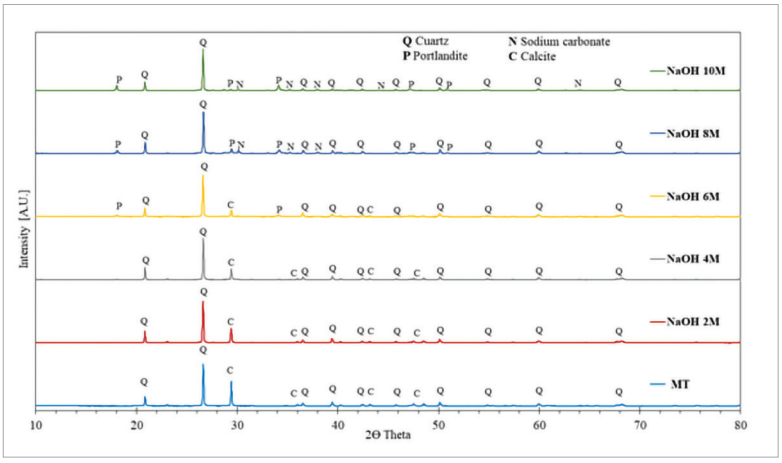


Fig. 4

XRD of MT and tailings activated with NaOH at different concentrations.

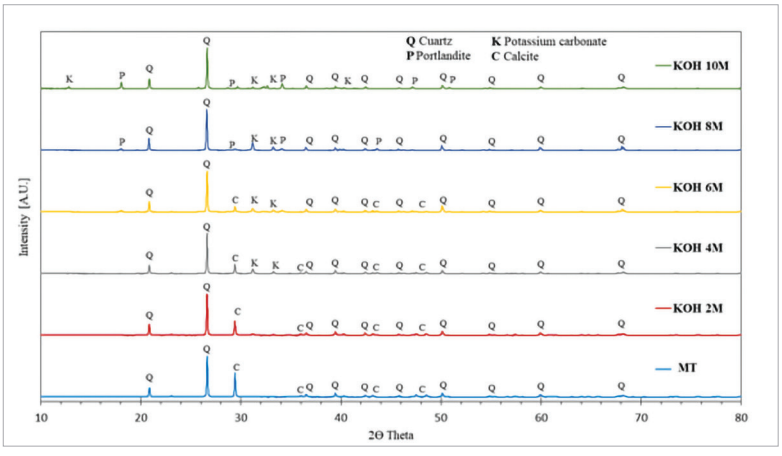


Fig. 5

XRD of MT and tailings activated with KOH at different concentrations.

Results

the presence of non-reactive quartz has shown good performance as a filler in the consolidation of geopolymers (Perera-Mercado et al., 2022), as it can provide nucleation sites for the dispersed formation of hydration products (De Oliveira Neto et al., 2021).

Mixtures with a concentration of 10 M are selected because X-ray diffraction (XRD) analysis revealed a significant reduction in calcite peaks and the appearance of portlandite phases, as illustrated in Fig. 4 and 5. This structural transformation suggests increased dissolution of the mineral phases and higher reactivity of the system. In tests previously developed in the present investigation, it was found that with concentrations lower than 10 M of activator the resistances achieved were low and when higher concentrations were used the resistances decreased even lower and efflorescence was generated in the specimens. Furthermore, the 10 M concentration gave the best results in terms of workability and compressive strength, supporting the use of a high molarity alkaline activator in the synthesis of geopolymers based on mine tailings.

Stirring time of MT activated at 10M

Following the molar concentration analysis, the stirring time was optimized for the alkali activation of MT at a concentration of 10M for both NaOH and KOH, Fig. 6, evaluating 15 min, 1 h, and 24 h using XRD analysis. Fig. 6 shows that 15 minutes of stirring with NaOH are sufficient to significantly reduce calcite peaks (mainly at 28º 2θ) and generate portlandite and sodium carbonate phases; no substantial differences were observed between 15 min and 24 h. Previous studies have determined that the presence of calcium in the form of portlandite promotes the formation of C-S-H type gels in alkaline systems (Huang et al., 2020; Sore et al., 2020), its presence is beneficial for the development of these gels, contributing to optimal mechanical strength. Consequently, only 15 minutes is enough to achieve the same changes as 24 hours.

Fig. 6
XRD of MT and tailings activated at 10 M with NaOH with different stirring times.

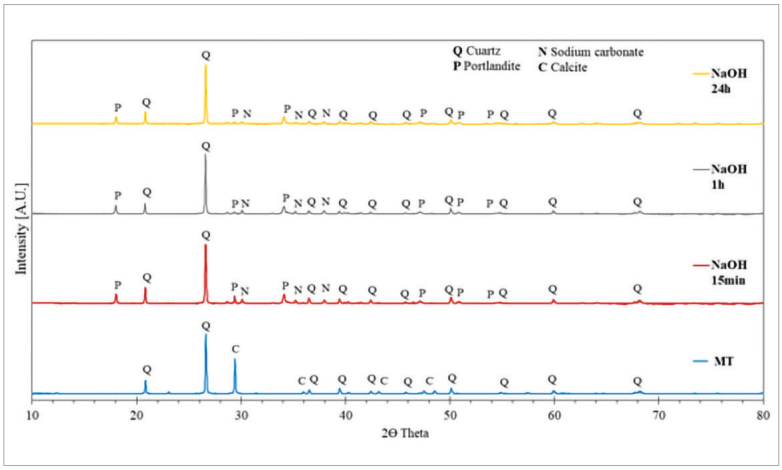


Fig. 7
XRD of MT and tailings activated at 10 M with KOH with different stirring times.

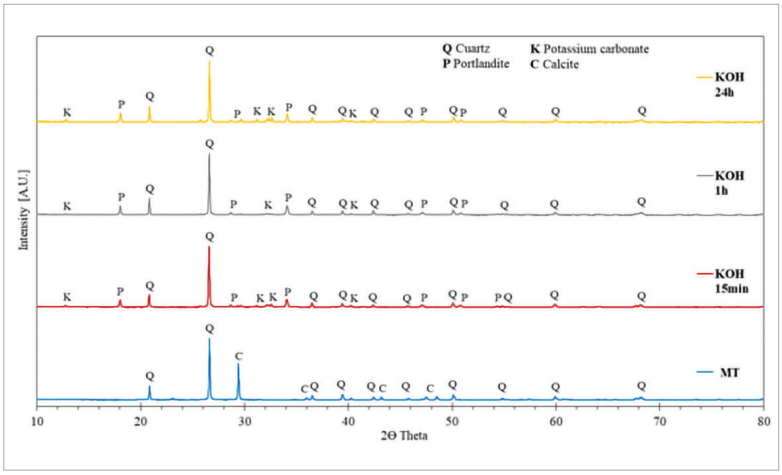


Fig. 7 presents the XRD patterns using KOH as an activator. Similar to the previous case, after 15 minutes of stirring, the calcite phase disappears, leading to the formation of portlandite and carbonate phases. No significant differences are observed in the reduction or disappearance of phases across the

three stirring times. Based on these findings, 15 minutes of stirring is considered an adequate activation time for preparing the pastes.

Compressive Strength of AAMs at 10M

Fig. 8 presents the variation in compressive strength of AAMs with NaOH and KOH at 10M, evaluated at 3, 14, and 28 days of curing. Specimens made without activator, using only water, showed a minimum strength of 1 MPa at 3 days, indicating a lack of inherent reactivity, confirmed by XRD analysis. In contrast, activated specimens achieved 12.7 MPa with NaOH and 10.5 MPa with KOH at 3 days. At 14 days, the strength of specimens without activator decreased to 0.9 MPa, while activated specimens increased their strength by approximately 3 MPa, reaching 15.3 MPa with NaOH and 13.4 MPa with KOH. At 28 days, the strength of specimens without activator continued to decrease to 0.8 MPa, while activated specimens showed an additional increase reaching 16.4 MPa with NaOH and 14.6 MPa with KOH, which resemble previously reported values (Surehali et al., 2023). The compressive strength reached due to the densification of the microstructure is explained by several factors (Palomo et al., 2014): the increased concentration of OH^- ions in the solution enhances the dissolution of Si and the release of Ca^{2+}, promoting the formation of C–(A)–S–H gels, the alkaline activator disrupts the water-impermeable layer on the surface of binder particles, accelerating reaction kinetics and increasing the formation of reaction products, and finally the formation of silica-rich gels due to a higher concentration of $[SiO_4]^{4-}$ ions.

It is important to note that no additives or cement were incorporated to achieve compressive strength; these results are solely attributed to the activation of tailings, in comparison to specimens without activator.

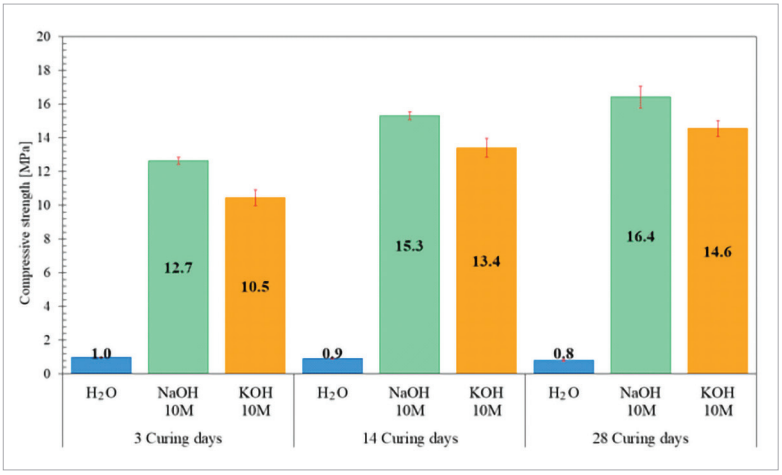


Fig. 8

Compressive Strength of AAMs from MT with NaOH and KOH at 10M.

Scanning Electron Microscopy (SEM)

Fig. 9a and 9b show micrographs of specimens activated with NaOH at 10M, cured for 28 days. The observed morphology presents flake-like structures composed of silicon, calcium, aluminum, and iron, characteristic elements of the precursor material. In systems with high calcium content, the C-A-S-H gel is the main reaction product, presenting a disordered structure similar to tobermorite (Garcia-Lodeiro et al., 2011), which resembles the structures observed in Figures 8a and 8b, as confirmed by EDS.

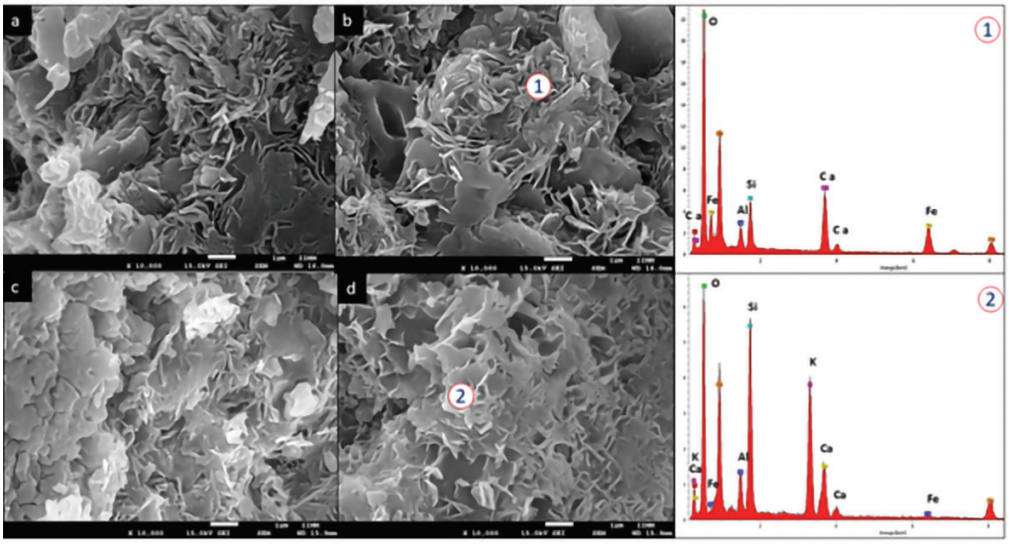
Figures 9c and 9d present micrographs of material activated with KOH at 10M, cured for 28 days. Scales and fiber-like structures rich in silicon and potassium are observed. The presence of high silicon peaks and the absence of unreacted particles suggest that silica contributes to the formation of silicoaluminous gels, which develop on the surface of the tailing particles (D'Elia et al., 2020; Mabroum et al., 2020). EDS analyses indicated that the material is primarily composed of silicon, potassium, calcium, aluminum, and traces of iron, elements present in the precursor materials.

The micrographs of the material revealed cementitious matrices primarily composed of Si, Al, Ca, and other elements, confirming the results obtained in XRF and XRD with proportions varying

depending on the activator used. EDS analyses indicated that the concentrations of silicon and calcium vary depending on the region analyzed in the matrix, suggesting the possible formation of mixed (N,C)-A-S-H/N-(C)-A-S-H gels (Jabar et al., 2025).

Fig. 9

Micrographs of AAMs with NaOH (**a** and **b**) and with KOH (**c** and **d**) at 10M, cured for 28 days.



Conclusions

XRF and XRD analyses conducted on mine tailings revealed a chemical composition suitable for the generation of Alkali-activated materials. The dissolution test of MT under different activator concentrations revealed that higher concentrations promote the reduction of calcite phases, with 10 M identified as the most suitable concentration. Quartz, due to its high crystallinity, showed limited dissolution; the calcite phase was completely dissolved. Stirring time for 15 minutes at 10 M proved sufficient to dissolve calcite, yielding similar results to longer times of 1 and 14 hours. This finding indicates that short activation times are adequate for processing the MT with both activators.

MT without activator mixed only with water exhibited low compressive strength, attributed to their crystalline structure, which limits reactivity. In contrast, activation with NaOH achieved the best performance, reaching a compressive strength of 16.4 MPa and confirming the technical viability of MT as a material for generating structural building elements. Considering the production and curing requirements of this material, a viable field of application is prefabricated components. These may range from small elements, such as tiles or partitions, to large units, such as beams or even walls, provided the appropriate infrastructure is available.

Microstructural analysis of AAMs evidenced the formation of hydration gels responsible for mechanical development. The proposed method is cost-effective, requires minimal activation time, and produces strengths compatible with constructions requirements. The findings indicate that incorporating activated MT could enhance the sustainability of construction materials.

Based on these results, future research could explore complementary variables such as other curing conditions and long-term durability to further enhance mechanical performance and environmental benefits.

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