Mine tailings-based geopolymers: Physical and mechanical properties

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Abstract

The mining sector generates a substantial quantity of stone waste and tailings, which constitutes an environmental risk. The most prevalent method for disposing of this industrial waste is dumping, which contributes to soil deterioration and water contamination while acquiring precious land. It can be recycled using a number of processes, such as the promising geopolymerization technique, which transforms waste into value. This study reviews current developments in the manufacturing of mine tailings-based geopolymer composites from industrial waste as a possible sustainable building material. This paper also gives in-depth studies on the characteristics and behaviors of mine tailings composites used in geopolymer manufacturing, including physical and mechanical properties. This review also identifies knowledge gaps that must be filled in order to advance mine tailings composites for geopolymers.

Keywords

Mine tailings; Industrial waste; geopolymer; Mechanical properties, Physical properties

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, 2]. 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, biota, polluting soils, air , and water , and causing cancer in humans . Pollutants from food processing and feed waste harm valuable farms and natural ecosystems . The functioning of tailing dams increases the likelihood of man-made catastrophes occurring [3, 4].

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 [5-10], 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% [11]. As a result, tailings have the potential to serve as an alternative source for meeting a wide range of construction and industry requirements [12-14].

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 [15-17]. Materials composed mostly of amorphous sodium aluminum-silicate hydrate are called geopolymers [18]. They are primarily solids formed by the interaction of an aluminosilicate powder and an alkali solution [19]. According to van Deventer, et al. [18], the geopolymer network is composed of AlO_4 and SiO_4 tetrahedra connected by oxygen atoms [19]; 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 [20-24]. 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 [25-27], sustainable building [28-32], and another particular usage [12, 29, 30, 33-41].

The mine tailings are inhomogeneous and have a complex mineral, aggregate, and chemical composition [11]. Furthermore, although having relatively low quantities of valuable components, mine tailings contain hazardous and toxic compounds connected with waste products or mining activities [42-46]. 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 [47, 48].

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. Physical properties

2.1. 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 [2-4, 12, 49]. 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 [50, 51], 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 [51, 52]. The workability loss of geopolymer composite binders depends solely on the volume fraction in the mixtures and the fiber aspect ratio [53]. The report of Savastano Jr, et al. [54] reveals a decline in the workability of cement composites in the presence of eucalyptus pulp, coir, or eucalyptus pulp in combination with sisal fibers [13-17].

The workability of alkali-activated tailing paste is influenced by a combination of factors like calcination temperature and water-to-tailings ratio. Savastano Jr, et al. [54] reported that sufficient workability at 800 ºC calcination requires water to waste clay containing a boron ratio of 0.40. For lower calcinations of 700 ºC, 600 ºC, and 500 ºC, 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 [55-58].

2.2. 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. 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. Most of the time, steam-curing affects things like the uniform distribution of hydration products and the porosity of Portland cement paste [59-62].

Aydın and Kızıltepe [63] 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 [55-59]. 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, et al. [64].

Falah, et al. [65] 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) [66]. 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 ºC and 60 ºC 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, et al. [67] 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 [68] [69, 70].

Regardless of tailings source or mineralogy/composition, grinding time is a major parameter influencing the water absorption capacity [71]. 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 one min. However, when the grinding time was increased to 16 minutes, 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 [72-76].

3. Mechanical properties

3.1. 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 [60-62, 72-75].

Barrie, et al. [77] 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, et al. [78], 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, et al. [79] 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 [80-82]. 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 to 62 weight% of precursor) displayed substantial chemical resistance. Table 1 presents a summary of the impacts of employing tailings as aggregates in geopolymer mixes [83, 84].

Table 1. 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	[79]
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	[85]
	fly ash-geopolymer composites	As fine aggregates	33.5	Lesesne the time required for setting; improve the compressive strength and density	[78]
	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	[86]
Gold	Volcanic glass-geopolymer composites & calcined Halloysite-geopolymer composites	As fine aggregates	12.50	There is no detrimental impact on the mechanical characteristics	[77]

Quartz	metakaolin - geopolymer composites	As admixture	10−32	Increase in viscosity; lowering in flowability and shrinkage during drying; no adverse impact on mechanical characteristics	[87]

3.2. 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 [88-90].

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 [28, 91-97] because of the uniformity and purity of its composition, as well as its high interaction [28, 76, 80-82, 88-90]. Falayi [98] 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 [25, 99]. Figure 1 shows a source of 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 [100-107]. 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 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 [108-110]. 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, et al. [111] after calcining bauxite tailings at 800 ºC for 1 hour, which increased the interaction of the mine tailings during geopolymerization. As shown in Fig. 2, after thermal treatment at almost 600 °C, Kiventerä, et al. [112] noted a decrease in the dolomite peak shown by gold tailings. When heated over 400 ºC, basanite transforms into anhydride. On the other hand, the quartz amount remained stable until 650 ºC, when it declined slightly [113-117].

As indicated in Tables 2 and 3 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 [113-120].

The curing temperature of mine tailings-geopolymer composites has a substantial impact on the mechanical and microstructural characteristics of the polymers. Tian, et al. [121] 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 ºC, on the other hand, had the opposite impact. The high curing temperatures (between 100 and 125 ºC) resulted in a lowering of the amount of alkaline medium present, which prevented the dissolution of silica and alumina types [118-120, 122].

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, et al. [123] 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 [124], Manjarrez, et al. [125] 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 [126], 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. 3 once the water content was exceeded. They also discovered that after being submerged in water, compressive strength dropped considerably. Additionally, Manjarrez and Zhang [127] 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 ºC also resulted in an improvement in the compressive strength of a copper mine tailings-geopolymer composite activated by sulfur dioxide [126, 128, 129].

When further alumina-silicate source materials are added, the compressive strength of copper mine tailings-geopolymer composites improves [125]. 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 [130, 131].

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 ºC and a rise in curing period up to 7 days, after which the compressive strength declined [132-134].

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 [135] 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 ºC enhanced the compressive strength of potassium aluminate and potassium hydroxide-activated gold mine tailings-geopolymer composites [122, 133, 134]. The researchers also discovered that the compressive strength of 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 ºC.

According to an investigation conducted by Pardavé, et al. [136], 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, et al. [137] 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. 4 [137].

Solismaa, et al. [138] 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 ºC. At 85 ºC, 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 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 [139, 140]. Jiao, et al. [141], Wei, et al. [142], 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 [143].

Ye, et al. [144] 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 ºC. 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, et al. [145] 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 [47, 48]. 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.

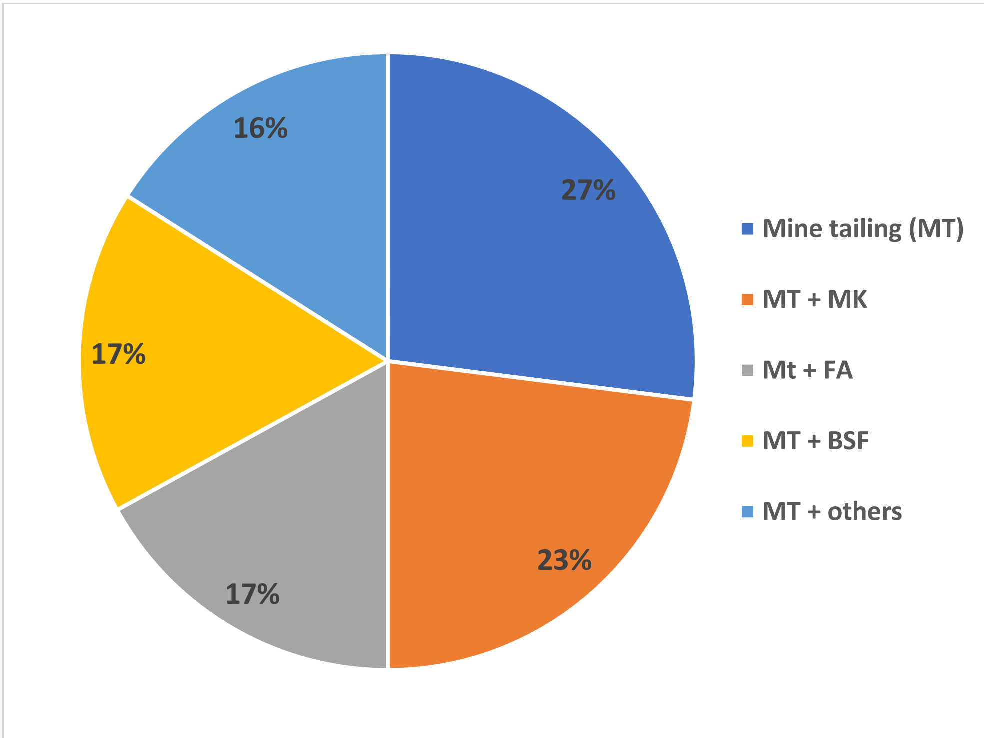
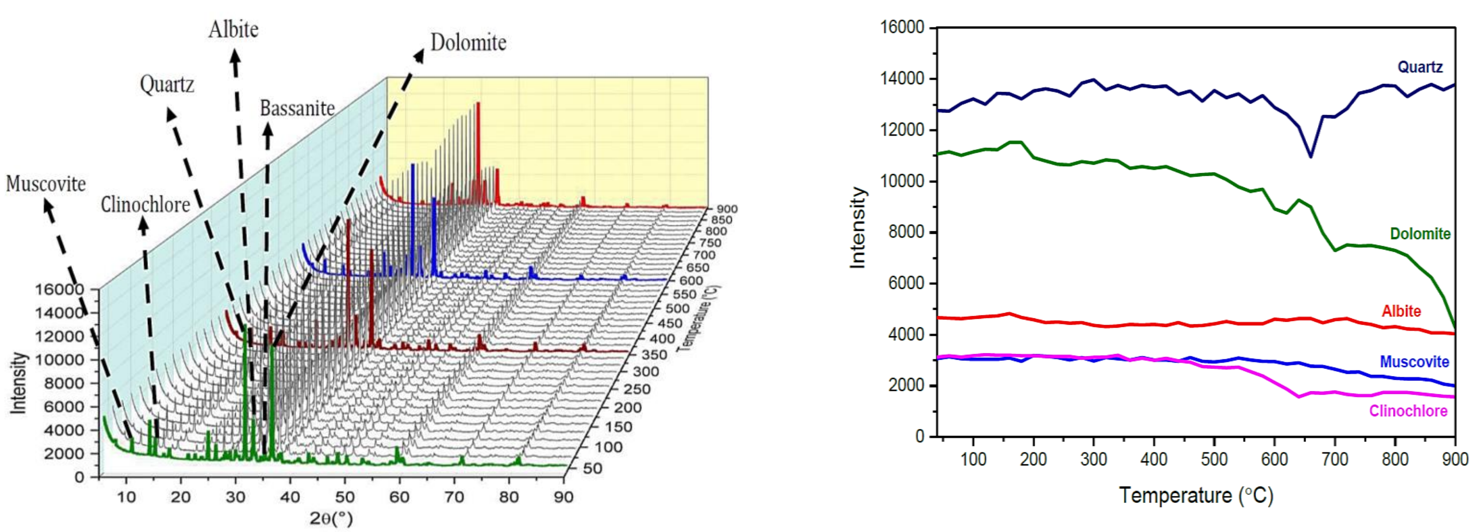


Fig. 1. Source of geopolymer precursors utilized with mine tailings for the production of mine tailings-geopolymer composites [11].



(a) (b)

Fig. 2. (a) XRD analysis of mine tailings through heat treatment; (b) Intensity variance for some main components [112].

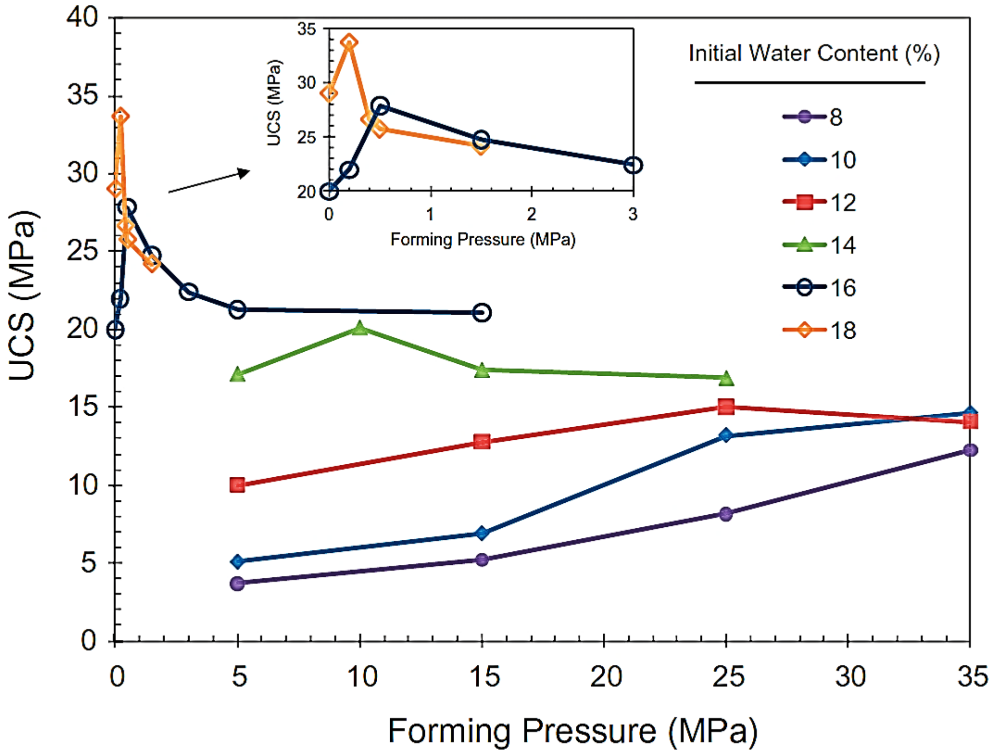


Fig. 3. Unconfined compressive strength (UCS) versus forming pressure for samples produced at varying water contents, including 15 molarity NaOH dosage and cured at 90 ºC for 7 days [146].

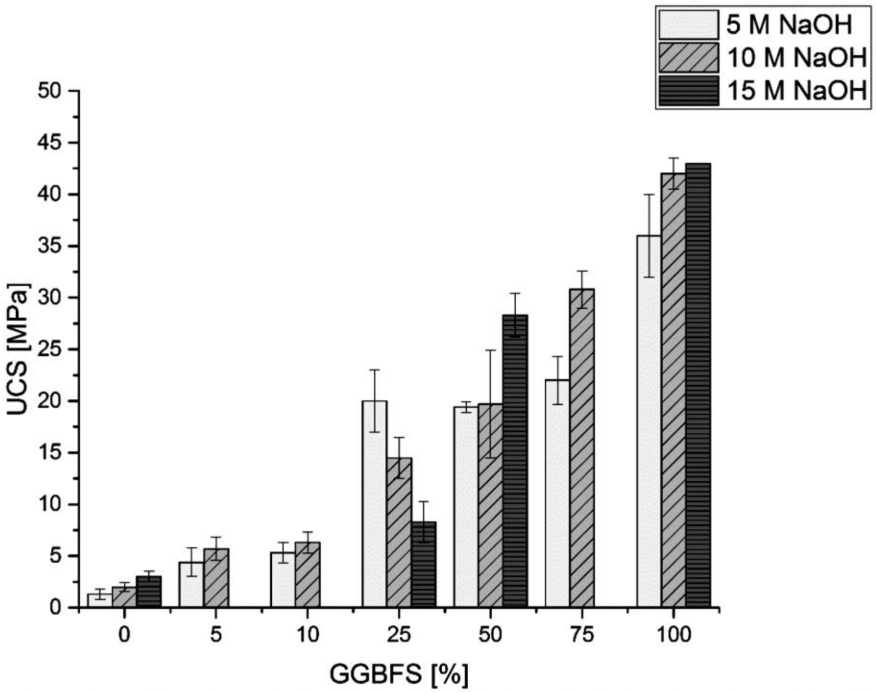


Fig. 4. Unconfined compressive strength (UCS) of bricks with varying GGBFS- and NaOH–content after 28 days [137].

Table 2. 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)	[111]
		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)	[144]
		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)	[125]
	-	-	SH	35	0.3–5.3 (7 d)	[127]

	Aluminum sludge	0-20	SH	95	11–45 (7 d)	[99]
	Low-Ca flash-furnace copper smelter slag	0-100	SH	65-105	1–76 (7 d)	[147]
	-	-	n.m.	n.m.	3–33.6 (7 d)	[131, 146]
	fly ash	0-100	SH	60	3–7 (2 d)	[148]
		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)	[79]
	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)	[149]
Gold	fly ash	0-50	-	-	1–12 (3 d)	[135]
	Basic oxygen furnace slag	0-50	-	-	1–22 (3 d)	
	BFS	10, 25	SS, SH & CH	Ambient	6–19 (28 d)	[79, 150]
Iron	-	-	SH	100	18–112.8 (7 d)	[151]
	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)	[152, 153]
	-	-	SS	80	1–34 (3 d)	[154]
		-	SS	80	50.5 (7 d)	
Kaolinite	-	-	-	40 & Ambient	12–15 (7 d)	[155]
Phosphate	metakaolin	30, 40	SS & SH	60 & Ambient	24–39.94 (28 d)	[28]
	-	-			4 (7 d)	[156]
		-	-	40 & Ambient	4–7 (7 d)	[155]
	metakaolin	50, 100	SS & SH	60, 85 & Ambient	12.8–53 (14 d)	[28, 157]
	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)	[87]
		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)	[140]
Tungsten	WG	0, 20, 30, 40	SS & SH	20-80 & 20	0.6–29 (1 d)	[158]

		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)	[159]
		N.M.	SS	Ambient	8.6–22.5 (7 d)	[142]
		N.M.	SS	Ambient	8.6–25 (14 d)	
		0, 10, 20, 30, 40	SH	20 & Ambient	10.8–55.6 (7 d)	[160]
Zinc	metakaolin	0, 10, 20, 30, 40, 50	SS	60 & Ambient	1.2–30.2 (7 d)	[139]

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).

Table 3. Flexure strength for several mine tailings-geopolymer composites.

Mine tailings type	geopolymer precursors	Content of precursors, (wt%)	Alkaline activators	Curing Tem (◦C)	Flexure strength (MPa), (Age-Days)	Refs
Bauxite	Slag	30	SS & SH	20	5.3 (3 d)	[111]
		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)	[144]
		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)	[151]
	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)	[87]
		70, 80, 90	KH & KS	20	2.0–2.5 (7 d)	

70, 80, 90	KH & KS	20	2.0–2.5 (28 d)

4. Conclusions

The key annotations for this paper review are as follows:

1. According to the results of the referenced study, 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.

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. Furthermore, natural radionuclides can be found in mine tailings in amounts that exceed the radiological safety criteria, which should be considered while employing mine tailings in geopolymers.

3. Several aspects impact how well mine tailings-geopolymer composites function, and the synergistic impact between some of them (like mineralogy, virtuousness, and element distribution) must be addressed in order to reap the greatest possible advantage from employing mine tailings.

4. 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. When compared to low-Ca-comprising additions, high-Ca-comprising elements have a more favorable impact on the geopolymer's overall strength and durability. This is induced by the production of extra CSH gels, which strengthen the matrix as a result of its co-existence with NASH, which improves the matrix density.

5. Supplemental materials, especially those with a lot of calcium, tend to be better at making geopolymer characteristics.

6. 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. Many times, the alkaline reactivity of mine tailings is extremely low, which is the best thing when mine tailings are used to make geopolymers.

5. Recommendations

The following are the main recommendations for future investigations:

1. 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.

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. Furthermore, natural radionuclides can be found in mine tailings in amounts that exceed the radiological safety criteria, which should be considered while employing mine tailings in geopolymers.

Conflicts of interest/Competing interests

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.

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