Case Studies in Construction Materials 16 (2022) e00933

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

# Recycling of mine tailings for the geopolymers production: A systematic review

Shaker M.A. Qaidi [a], Bassam A. Tayeh [b,*], Abdullah M. Zeyad [c], Afonso R. G. de Azevedo [d], Hemn Unis Ahmed [e], Wael Emad [f]

[a] Department of Civil Engineering, College of Engineering, University of Duhok, Duhok, Kurdistan Region, Iraq
[b] Civil Engineering Department, Faculty of Engineering, Islamic University of Gaza, P.O. Box 108, Gaza Strip, Palestine
[c] Civil Engineering Department, College of Engineering, Jazan University, Jazan, Kingdom of Saudi Arabia
[d] UENF - State University of the Northern Rio deJaneiro, LECIV – Civil Engineering Laboratory, Av. Alberto Lamego, 2000, 28013-602 Campos dosGoytacazes, RJ, Brazil
[e] Civil Engineering Department, College of Engineering, University of Sulaimani, Sulaimaniyah, Kurdistan Region, Iraq
[f] Department of Civil Engineering, Komar University of Science and Technology, Kurdistan-Region, Iraq

ARTICLE INFO

*Keywords:*
Industrial waste
Mine tailings
Geopolymer
Economic and ecological perspective
Mechanical, durability, microstructure, and thermal properties
Applications

ABSTRACT

The mining sector generates a considerable amount of waste stone and tailings, which constitute a substantial hazard to the ecology. The most prevalent method of disposing of these industrial wastes is by dumping, which adds to soil deterioration and water contamination and also takes up valuable land. Fortunately, it can be recycled in a variety of ways, including the promising geopolymerisation technique, which converts waste into value. This article discusses recent advances in the production of mine tailings-based geopolymers composites (MT-GPC) from waste and industrial by-products as a potentially sustainable construction material. Besides, focusing on the following aspects: economic and production perspective; environmental consequences and waste disposal; physical and chemical properties; mechanical properties; durability properties; microstructure properties; thermal properties; and potential applications of MT-GPC.

## 1. Introduction

Mine tailings (MT) collect in tailings ponds and mine waste (MW) landfills, and the challenge of sustainable disposal of these wastes is becoming considerably more critical [1–7]. This is because the metallurgical and mining industries have increased their producing volumes, as well as the absence of appropriate methods for disposing of the wastes generated by these industries, on one side. On the other side, 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 MT-related toxins are actively released into the ecological as a result of the buildup of tailings [8–11], biota [12–19], polluting soils, air [20–25], and water [26–31], and causing cancer in humans [32–40]. Waste from the preparation of food and feed contaminates contributes to the condemnation of valuable farmland and natural landscapes [32,41]. The functioning of tailing dams rises the likelihood of man-made catastrophes occurring [18, 42–49].

* Corresponding author.
*E-mail address:* btayeh@iugaza.edu.ps (B.A. Tayeh).

https://doi.org/10.1016/j.cscm.2022.e00933
Received 24 December 2021; Received in revised form 27 January 2022; Accepted 6 February 2022
Available online 7 February 2022
2214-5095/

Moreover, from the perspective of rational natural source management, MT should be regarded as a mineral source that has been removed from the Earth's subsurface, has been relocated, and has been underused. The tailings may include trace amounts of target material, as well as previously unclaimed elements that can be restored with the use of more effective mining techniques [42,50–54], which is one reason for this viewpoint. The chemical composition of MT, on the other hand, formation predominantly of silicon, aluminium, and calcium oxides, with a content ranging from 60% to 90% [55]. As a result, tailings have the potential to serve as an alternative source of meeting a wide range of construction and industry requirements [25,42,56–71].

A potential trend in the application of MT appears to be the utilization of MT as geopolymers (GPs) and precursors of alkali-activated (AA) materials or aggregates [72–79]. Geopolymers are materials composed mostly of amorphous sodium aluminum silicate hydrate [80,81]. They are primarily solids formed by the interaction of an alumino-silicate powder and an alkali sol [82,83]. According to [80], the geopolymer network is composed of $AlO_4$ and $SiO_4$ tetrahedra connected by oxygen atoms [82]; the negative charge is balanced by positively charged ions (e.g., $Ca^{2+}$, $Na^{+}$, $K^{+}$, and $Li^{+}$) existing in the cavity framework. It is possible that utilization of MT as GPs approach will not only slow down the accumulation of MT and lower the level of ecological contamination, but it will also combine the advantages of GP technology associated with a lowering in carbon dioxide release into the environment, the potential of utilizing other forms of techniques alumino-silicate waste, and the versatility of GPs characteristics as a general-purpose construction adhesive [84–89]. Lately, there has been a noticeable surge in awareness among a varied set of experts in the management of tailings in standard practices. Over a dozen publications have been published highlighting the efforts undertaken to improve our understanding of the geopolymerisation processes of tailings in order to regulate the characteristics of GPs for applications like pollutant removal [90–92], sustainable building [63,64,93–95], and other particular usage [63,94,96–105].

The MT are inhomogeneous and have a complex mineral, aggregate, and chemical component [55]. Moreover, comprising comparatively low quantities of useful components, MT includes dangerous and toxic substances that are associated with waste products or mining processing [75,77,106–108]. All of these factors make it more difficult to manage MT directly in order to obtain GPs that meet ecological safety criteria in respect of impurity content while also achieving the essential complex functional characteristics for the manufactured product.

As a result, resolving the issues associated with the utilization of MT-GPC is extremely useful, both in terms of lessening the negative impact on the ecology or in terms of the probability of expanding the resources base of man-made mineral raw substances. Solving the issues associated with the utilization of MT-GPC is particularly useful.

This review begins with a discussion of some of the physicochemical and ecological issues of the utilization of MT-GPC. MT-GPC


**Fig. 1.** Advantages of utilization MT in geopolymers [55].

are discussed in length in this paper, which is both a generalisation and a thorough investigation of the link between its structural, mechanical, and thermal capabilities, as well as its durability, and other substantial aspects. Apart from the useful features of the formation of the characteristics of MT-GPC, we discuss comprehensively the well-known cases of its utilization of promising applications.

## 2. Economic and production perspective

Among the characteristics of the mining sector are a substantial consumption of energy resources and materials, a minimal rate of mining of technically and commercially useful metals (between 1% and 4%), and a major impact on the ecological [109]. Some reports state that around 19–25 billion tons of solid MW are generated yearly across the globe, with 5–8 billion tons of MT [110,111]. Additionally, the expansion of the mining region necessitates the development of infrastructures to encourage extracting operations. Accordingly, MT become a useful source for its utilization of sustainable construction materials like GPs. Every two years, the number of publications increases by two times [3,112], as well as a new resource of production of metal that permits for the resolution of both the economic and ecological issues associated with MT disposal [113].

Following is a summary of the key production and economic considerations that should be taken into account when utilizing MT-GPC, as seen in Fig. 1. The production of MT-GPC is economically viable if the transporting costs incurred by customers of MW are kept to a minimum. Substantial consideration should be given to the geographic closeness of the mining operation to the expected customers of MT as well as the regions of consumption of final GP products in this respect. These features help to lower the capital and operational expenditures (by about 44%) associated with the development of MT, as well as the negative impact on the ecological.

MT-GPC are economically efficient as compared to other substances because it lessened the amount of expenditures experienced by consumers of MW for transportation. The closeness of the mining firm to the targeted customers as well as the locations where finished GP products will be consumed are critical considerations for the mining enterprise. These aspects help to lower the initial and operational expenses associated with the development of MT.

## 3. Environmental consequences and waste disposal

The disposal of MT is one of the most substantial causes of ecological damage caused by the mining industry. This is not unexpected given the fact that the amount of mine tailings that must be kept often surpasses the amount of ore that can be extracted in situ. Over the past century, the amount of MT has expanded considerably as a result of the growing demand for metals and minerals, in addition to the adoption of better mining and processing processes to utilize low-grade minerals and extract more value from them. A recent report published by the Chinese Academy of Land and Resources Economics estimates that China's mining tailings pile stock was around 21 billion tons at the end of 2018. If MW is not properly disposed of, it may lead to serious ecological consequences like acid mine drainage, dust mobilization, heavy metal buildup in biological communities, and soil contamination as shown in Fig. 2.

As a result of this ecological load, it is essential to dispose of MT in a fair manner as shown in Fig. 3. A substantial portion of the

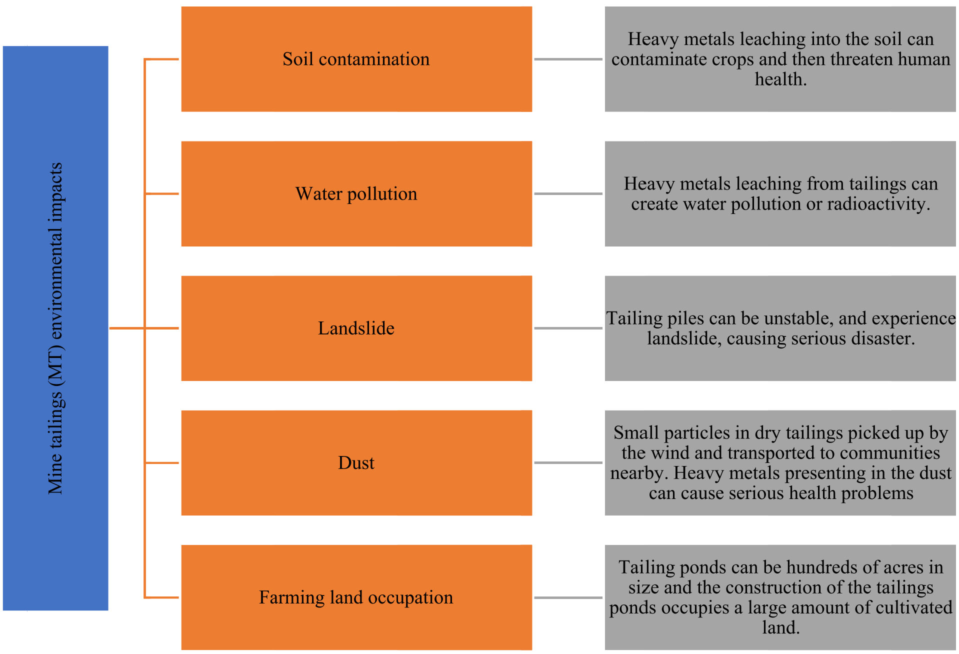


**Fig. 2.** MT environmental impacts [116].

past research has ↱concentrated on recycling main tailings as a backfill cement paste [60]. Surface ↱MT are often combined with a binder in a small backfill factory before being transferred ↱to subterranean stopes through gravity and/or pumping [114]. The amount of ↱mining tailings that must be kept in tailings ponds is lessened as a result of this method ↱↱[115]. It is possible to alleviate the difficulties connected with MT, such ↱as dust production, landslides, surface water contamination, and the occupancy of farmed land by ↱MT. Furthermore, valuable components may be retrieved from MT that were ↱previously dumped; for instance, silver- and lithium-comprising ↱minerals can be collected from gold and micaceous tailings, respectively. Many forms of MT have potential for recycling and re-use, ↱including Mn-rich tailings, which can be utilized to manufacture building materials, ceramics, glass, and coatings; clay-rich tailings, which can be utilized to manufacture bricks, sanitary wares, porcelain, and cements; iron ore ↱tailings mixed with supplementary materials, like fly ash (FA) and sewage; bauxite-comprising tailings, which can be utilized as Al resources. These disposal ↱techniques assist mining businesses in cleaning up existing MT and converting them into ↱something of value for the company. But any recycling or re-use of MT needs a realistic ↱evaluation of the pollutants that they may release; consequently, complete knowledge of the ↱ geochemical, mineralogical, and bulk physical characteristics of MT is required before ↱they can be safely disposed of in the environment. ↱.

## 4. Physical and chemical properties of MT

In the mining industry, MT are a fine-grained blend of ground-up stone particles ↱and processing effluents, which are produced as a byproduct of the mining of ↱precious minerals and metals from mined ore [63,76,117–123]. During the process of ore beneficiation, more than half of the overall ore bulk is ↱converted into tailings.↱

The constancy of the MT might vary greatly relying on the technique of beneficiation ↱and storage utilized – from a slurry state to a thickened paste state and finally to a dry state, ↱relying on the method of storage and beneficiation utilized. The content of solids of each of these ↱ types can range from 15% to 86% or more, relying on the types as shown in Table 1. GPs ↱are often prepared from dehydrated tailings, which may be obtained either by dry preparation ↱procedures or by simply drying the MT paste or slurry, followed

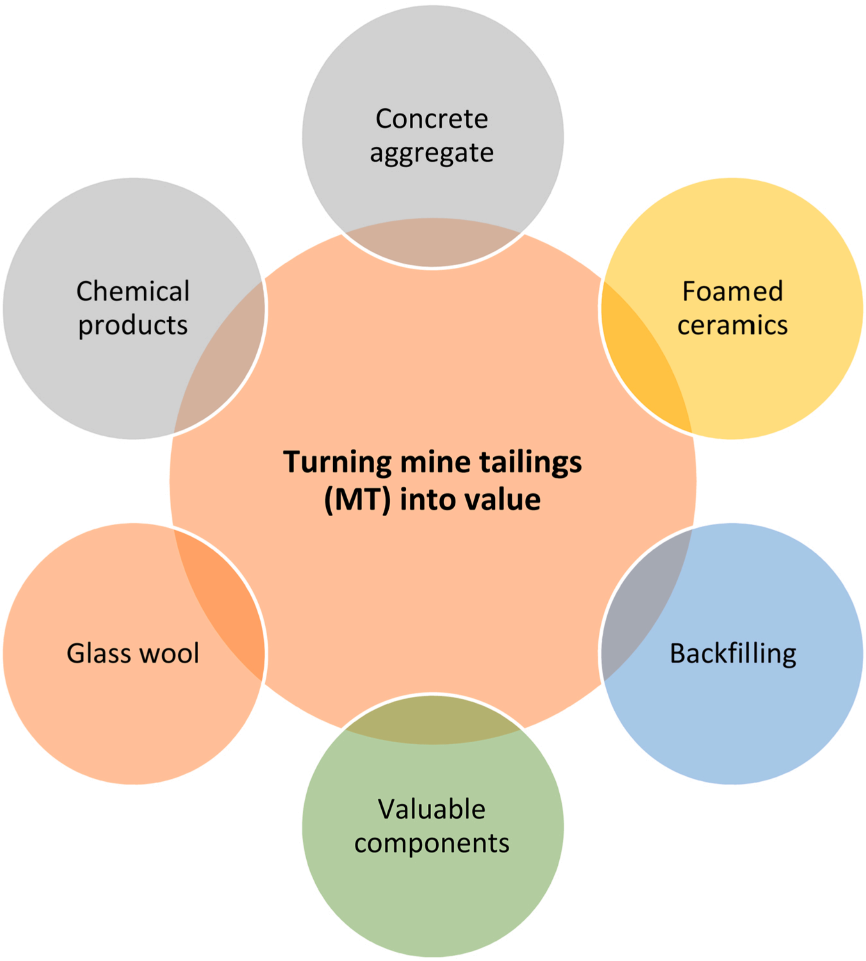


**Fig. 3.** Techniques for turning MT into value [116].

by grind [91,123,124].

MT utilized in GPs are primarily composed of a combination of mineral particles of varying sizes – ranging from silt and clay fractions to heavy sandy fractions – with varying degrees of agglomeration. In addition to grinding processes and mineral processing technologies, the particle-size distribution of tailings is influenced by the hardness of the minerals included in the stones, as demonstrated by Sternal, Junttila, Skirbekk, Forwick, Carroll and Pedersen [125], Duan, Yan, Zhou and Ren [126], and Cao, Wang, Yin and Wei [127]. In general, the particle form of most tailings is non-rounded, angular, and irregular, which is the consequence of crushing and grinding throughout the ore processing process. The specific surface area of MT, which ranges between 0.5 and 7.3 $m^2/g$ and is impacted by the distribution and particle shape, is measured.

The bulk density of MT in the bulk state ranges from 1.81 to 1.93 $t/m^3$, with the average value being 1.81 $t/m^3$. These values rise in proportion to the depth of the MT or dumps in question [117,128,129]. It has been demonstrated that the density of tailings changes relying on the type of mineral raw sources utilized [130]. Because its pH differs from that of the parent mineral, MT can fall into either the acidic or basic ranges.

The MT employed in the manufacture of GPs, as seen in Tables 2, 3, exhibits a high degree of inhomogeneity in its characteristics. Because of the characteristic of the ore, the form of process fluids (surfactants and other reagents) utilized in the beneficiation process, the degree of mining of a target substance, and physical and chemical transformations that occur during the storage of MT, the chemical composition of tailings are varying.

As shown in Table 2 and Fig. 4, it was observed that the dominant compounds in MT in all instances are: $Al_2O_3$, $SiO_2$, $Fe_2O_3$, CaO, MgO, $Na_2O$, and $K_2O$. Besides, MT may contain up to 21% of contaminants in the form of salts, organic compounds, or both.

The chemical composition of MT is marked by having a broad range of values of some components even within the same mine as shown in Table 2. It is most likely that the observed variation in chemical and mineral composition is attributable to the inherent inhomogeneity of the host stone that houses the ore deposit. This should also be taken into consideration while putting together the GP's final composition.

## 5. Mechanical properties of MT-GPs

### 5.1. MT as aggregates for GP

MT, a waste comprising finely distributed silica, might be regarded aggregates of GP and AA materials because of its high silica content. MT recycling, in conjunction with the diminution of the ecological burden from MW, is intended to lower the cost of GP concrete while also protecting natural mineral sources. .

Barrie, Cappuyns, Vassilieva, Adriaens, Hollanders, Garcés, Paredes, Pontikes, Elsen and Machiels [159] utilized gold mining tailings as fine aggregates to substitute cement standard sand in a GP based on volcanic and halloysite glass. It has been established that the incorporating of 12.7% MT to the GP has no impact on the mechanical characteristics of the material. When geopolymerisation was completed, the resultant specimens exhibited good immobilization of Zn and Pb, but Cu showed enhanced mobility as a result of the high pH present during the process.

A GP mortar made of metakaolin (MK) and quartz was developed by utilizing iron MT to substitute natural quartz material. As was seen in the previous investigation, the introduction of MT had no substantial impact on the mechanical characteristics of the GPs. In contrast to the reference specimens (with quartz aggregate), the specimens comprising MT were recognized by increased porosity and water absorption than the reference specimens. This might have a detrimental impact on the material's durability. A similar investigation was performed by Sharath, Shivaprasad, Athikkal and Das [137] for fly ash-based geopolymer composite (FA-GPC), and the results were promising. As seen in this instance, the incorporating of iron MT resulted in a lowering in the setting time and a rise in the density of the matrix. The greatest compressive strength of GP specimens including MT was 8.3 MPa, while the maximum compressive strength of reference specimens comprising natural sand was 4.9 MPa. For instance, Paiva, Yliniemi, Illikainen, Rocha and Ferreira [139] employed high-sulfidic MT as a fine aggregate of metakaolin-based geopolymer composite (MK-GPC) or blast furnace slag-based geopolymer composite (BFS-GPC) to create a fine aggregate of GPs. A stronger compressive strength (>20 MPa) and a more rapid reactive nature were observed in MK-based geopolymers compared to BFS-based geopolymers. Furthermore, when

**Table 1**
Overview of the physical and chemical properties of MT that have been reported in the literature [90,110,117,121,131–139].

| Characteristic type | | Value |
|---|---|---|
| Specific gravity (g/cm3) | | 2.60–2.95 |
| Density ($t/m^3$) | | 1.80–1.95 |
| Solids bulk content (%) | Thickened tailings | 46–75 |
| | Tailing's slurry | 15–36 |
| | Dehydrated tailings | < 84 |
| | Paste tailings | 72–86 |
| Surface Area ($m^2/g$) | | 0.50–7.20 |
| Porosity (%) | | 35–45 |
| pH | | 2.60–2.95 |
| Particle-size distribution (μm) | | 1–2000 |

**Table 2**
The chemical compositions of various MT that are utilized to production GPs.↱.

| *MTtype* | *Country* | *$SiO_2$* | *$Fe_2O_3$* | *$Al_2O_3$* | *CaO* | *MgO* | *$Na_2O$* | *$K_2O$* | *$P_2O_5$* | *$V_2O_3$* | *V2O5* | *$SO_2$* | *$TiO_2$* | *$SO_3$* | *ZnO* | *MnO* | *CuO* | *BaO* | *PbO* | *LOIa* | *Others* | *Refs* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Copper | China | 28.20 | 57.83 | 4.25 | 1.91 | 1.15 | 0.52 | 0.80 | – | – | – | – | 0.32 | – | – | – | – | – | – | – | – | [141] |
| | China | 58.5 | 10.8 | 13.3 | 5.4 | 1.9 | 2.8 | 4.0 | – | – | – | – | – | 0.6 | – | – | – | – | – | – | – | [133] |
| | USA | 55.8 | 3.07 | 14.11 | 2.27 | 1.77 | 3.02 | 3.88 | 0.19 | – | – | 2.26 | 0.50 | – | – | 0.067 | – | – | – | – | – | [142] |
| | USA | 64.8 | 4.33 | 7.08 | 7.52 | 4.06 | 0.9 | 3.26 | – | – | – | – | – | 1.66 | – | – | – | – | – | – | – | [79] |
| | 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 | [143] |
| 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 | [144] |
| | Africa | 63.8 | 16.2 | 5.5 | 3.2 | 4.3 | 1.2 | 0.6 | 0.1 | – | 0.01 | – | 0.3 | – | – | 0.1 | < 0.01 | – | – | 4.8 | 0.13 | [143] |
| | Turkey | 89.22 | 0.84 | 6.2 | – | 0.29 | – | 1.24 | – | – | – | – | – | 0.09 | – | – | – | – | – | – | – | [91] |
| | Finland | 49.9 | 9.2 | 10.4 | 11.8 | 6.8 | – | 1.2 | – | – | – | – | 1.2 | – | – | – | – | – | – | 13.6 | – | [145] |
| Iron | Brazil | 40.0 | 48.9 | 8.7 | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | 6.0 | 1.8 | [124] |
| | China | 34.72 | 12.32 | 16.22 | 7.64 | 8.92 | 0.55 | 1.52 | – | – | – | – | 0.30 | – | – | 0.13 | – | – | – | 13.18 | – | [121] |
| | Australia | 57.30 | 25.12 | 9.57 | 0.03 | 0.07 | 0.05 | 0.04 | – | – | – | – | 0.61 | 0.16 | – | – | – | – | – | 6.67 | – | [132] |
| Phosphate | Finland | 32.98 | 7.98 | 7.08 | 12.92 | 17.28 | – | 5.53 | 0.96 | – | – | – | 0.27 | – | – | 0.12 | – | – | – | 14.01 | 0.88 | [146] |
| | Morocco | 23.5 | 1.53 | 3.55 | 31.12 | 4.16 | 0.54 | 0.46 | 14.1 | – | – | – | – | – | – | – | – | – | – | 19.3 | – | [93] |
| | Morocco | 22.8 | 0.85 | 2.5 | 34.3 | 4.1 | 0.9 | 0.4 | 14.0 | – | – | – | – | – | – | – | – | – | – | 19 | – | [147] |
| Vanadium | China | 83.47 | 2.42 | 5.09 | 0.96 | 0.65 | 3.25 | 0.66 | – | 0.23 | – | – | – | – | – | – | – | – | – | 1.25 | – | [148] |
| | China | 61.92 | 4.13 | 7.35 | 6.52 | 1.24 | 2.68 | 1.25 | – | – | 0.42 | – | 0.46 | 7.15 | – | – | – | – | – | 6.93 | – | [134] |
| | China | 64.17 | 4.99 | 10.27 | 4.48 | – | 5.27 | 2.07 | – | – | 0.14 | – | – | – | – | – | – | – | – | 1.15 | – | [149] |
| Kaolinite | Finland | 72.55 | 1.90 | 16.44 | 0.05 | 0.83 | 0.08 | 3.06 | – | – | – | – | – | – | – | – | – | – | – | 4.42 | 0.74 | [150] |
| Lead-zinc | China | 62.09 | 2.73 | 4.35 | 20.45 | 0.56 | – | 0.55 | – | – | – | – | 0.20 | 3.63 | – | – | – | – | – | – | – | [60] |
| Garnet | China | 44.28 | 13.82 | 5.57 | 30.26 | 0.81 | 0.23 | 0.13 | – | – | – | – | – | – | – | – | – | – | – | – | – | [151] |
| Lithium | Finland | 78.45 | 0.51 | 12.56 | 0.30 | 0.15 | 4.44 | 2.81 | – | – | – | – | – | – | – | – | – | – | – | 0.20 | 0.58 | [150] |
| Bauxite | China | 32.25 | 8.66 | 37.39 | 3.16 | 0.85 | 0.86 | – | – | – | – | – | 2.31 | – | – | – | – | – | – | 13.74 | – | [118] |
| Hematite | USA | 68.77 | 28.13 | 0.87 | 0.28 | 0.74 | 0.03 | 0.04 | – | – | – | – | 0.05 | – | – | – | 0.001 | 0.02 | – | – | 0.07 | [152] |
| Quartz | China | 97.48 | 0.30 | 1.11 | 0.17 | 0.22 | 0.04 | 0.02 | – | – | – | – | – | – | – | – | – | – | – | – | – | [153] |
| 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 | – | [154] |
| Tungsten | Portugal | 47.85 | 9.97 | 21.07 | 0.85 | 1.01 | 1.32 | 4.12 | – | – | – | – | 0.66 | 8.73 | – | – | – | – | – | – | – | [155] |
| 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 | [154] |

**Table 3**
The mineralogical composition of various MT utilized in the production of GPs.↱.

| Tailing types | Country | Mineralogical components (%) | Refs |
|---|---|---|---|
| Copper | South Africa | Chlorite (13.2), calcite (1.65), hematite (1.14), epidote (22.7), muscovite (4.7), hornblende (3.25), quartz (49.55), plagioclase (7.60) | [143] |
| | USA | Not reported | [156] |
| | China | Not reported | [133] |
| | China | Not reported | [157] |
| Gold | South Africa | Chlorite (2.95), anthophyllite (6.0), jarosite (7.70), hornblende (14.10), plagioclase (13.25), magnetite (3.65), sepiolite (9.35), quartz (42.95) | [143] |
| | Finland | Not reported | [143] |
| | South Africa | Not reported | [144] |
| Phosphate | Morocco | Quartz (12.5), fluorapatite (34.1), calcite (11.16), dolomite (9.46), kaolinite (9.45), hematite (1.5), plagioclase (21.2) | [93] |
| | Morocco | Quartz (18), fluorapatite (45), calcite (16), dolomite (72) | [76] |
| | Finland | Calcite (15), dolomite (5.95), feldspar (1.5), phlogopite (64), albite (0.98), actinolite (1.0) | [150] |
| | Finland | Calcite (13), dolomite (7), tremolite (1.5), phlogopite (65) | [146] |
| Iron | China | Not reported | [158] |
| | Brazil | Not reported | [124] |
| Kaolinite | Finland | Quartz (28), kaolinite (20.5), muscovite (43), | [150] |
| Sphalerite | China | Dolomite (45.70), quartz (3.70), kaolinite (5.20), calcite (35.25) | [154] |
| Garnet | China | Not reported | [151] |
| Lithium | Finland | Albite (38), quartz (37), microcline (15.8), muscovite (6.5), plagioclase (1.3), spodumene (2.7) | [150] |
| Vanadium | China | Not reported | [134] |
| Tungsten | Portugal | Not reported | [155] |
| Bauxite | China | Not reported | [118] |

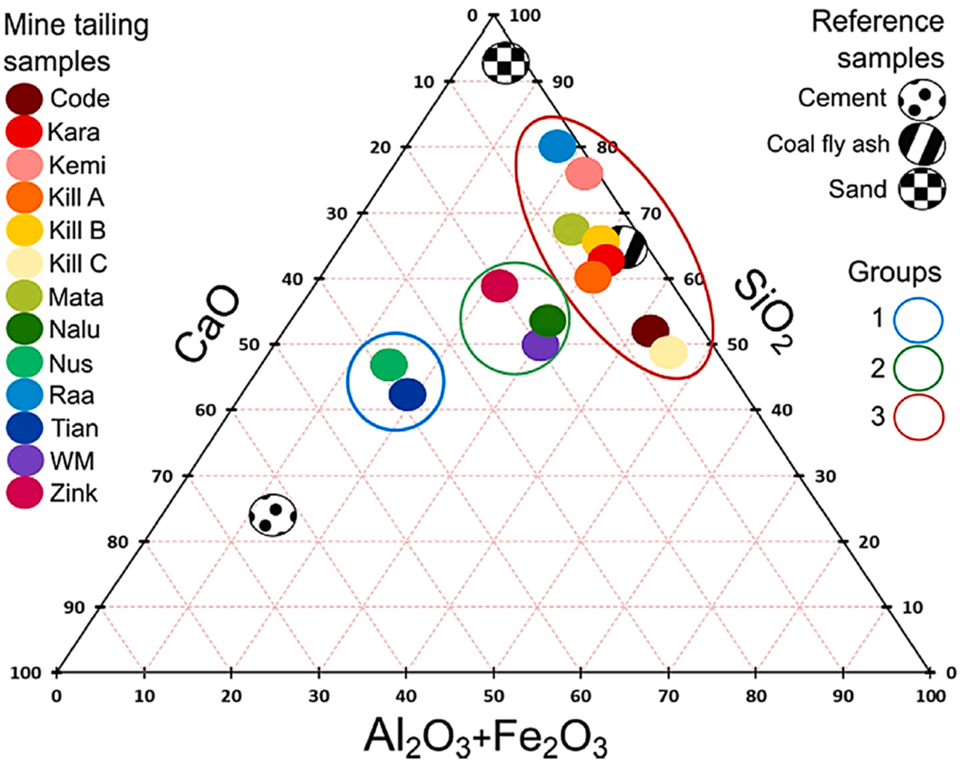


**Fig. 4.** Ternary phase diagram of the chemical composition of MT and each of cement, coal FA, and sand [140].

evaluated ↱under extremely harsh circumstances (pH 4 and 7 for 40-d), the compositions comprising a ↱high concentration of MT (50–62 wt% of precursor) displayed substantial chemical ↱resistance. Table 4 presents a summary of the impacts of employing tailings as aggregates in ↱GP mixes.

**Table 4**
Summary of the impacts of employing tailings as aggregates in ↱GP mixes.

| MT Types | GP precursors | MT in GP blends | MT replacement (wt %) of precursor | MT Impacts | Refs |
|---|---|---|---|---|---|
| Copper, zinc | BFS-GPC & MK-GPC | As admixture | 50–65 | Enhancing chemical resistance; altering the rheological characteristics | [139] |
| Iron | FA-GPC | As admixture | 10–35 | Improved setting time and workability; increased compressive strength and heat resistance; dropped porosity and microcracking's | [158] |
| | FA-GPC | As fine aggregates | 33.5 | Lesesne the time required for setting; improve the compressive strength and density | [137] |
| | MK-GPC | As fine aggregates | 50 or 100 | There is no impact on the mechanical characteristics; nevertheless, the porosity and water absorption are increased | [160] |
| Gold | Volcanic glass-GPC & calcined Halloysite-GPC | As fine aggregates | 12.50 | There is no detrimental impact on the mechanical characteristics | [159] |
| Quartz | MK-GPC | As admixture | 10–32 | Increase in viscosity; lowering in flowability and shrinkage during drying; no adverse impact on mechanical characteristics | [153] |

### 5.2. *MT as precursors for GP*

A variety of chemical characteristics distinguish the minerals that make up the makeup of mine ↱tailings, including their interaction with alkalis. The alumino-silicate↱ framework of the GP is ↱determined by the interaction of the mineral ingredients of the precursor in an AA sol, as ↱well as the structure and characteristics of the GP itself. In general, the alkaline interaction ↱of MT is low, and this is the most substantial factor to consider when incorporating MT into ↱GPs.↱

MT have a high silica content as shown in Table 2, which raises the molar proportion $SiO_2/Al_2O_3$ in ↱ MT-GPC, which has a detrimental impact on the geopolymerisation process. For this ↱reason, MK is the most often utilized as a supplementary source of Al in the chemical ↱industry [58,93,161–166] because of the uniformity and purity of its ↱composition, as well as its high interaction [93].↱ Falayi [144] has indicated that FA 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 aluminium oxide and aluminium sludge, calcined halloysite, and low-calcium slag [90,167]. Fig. 5 presents the resource of GP precursors utilized with MT to the production of MT-GPC.

MT-GPC exhibit a wide range of strength and deformation ↱characteristics, which are governed by a variety of parameters, comprising the Si/Al proportion, particle-size, ↱kinds of AAs, AA/binder proportions, and curing method. It is crucial to note ↱that the increased interaction of MT in geopolymerisation has an impact on the mechanical ↱characteristics of GPs, which is a useful consideration in the utilization of MT in ↱geopolymerisation. Because of the poor interaction of MT, extra pre-treatment processes ↱are required. Pre-treatment of MT, like mechanical activation, calcination, and alkali ↱melting, has also been shown to have a favorable impact on its interaction and the subsequent ↱GP, owing to the microstructural and mineralogical alterations that occur during these

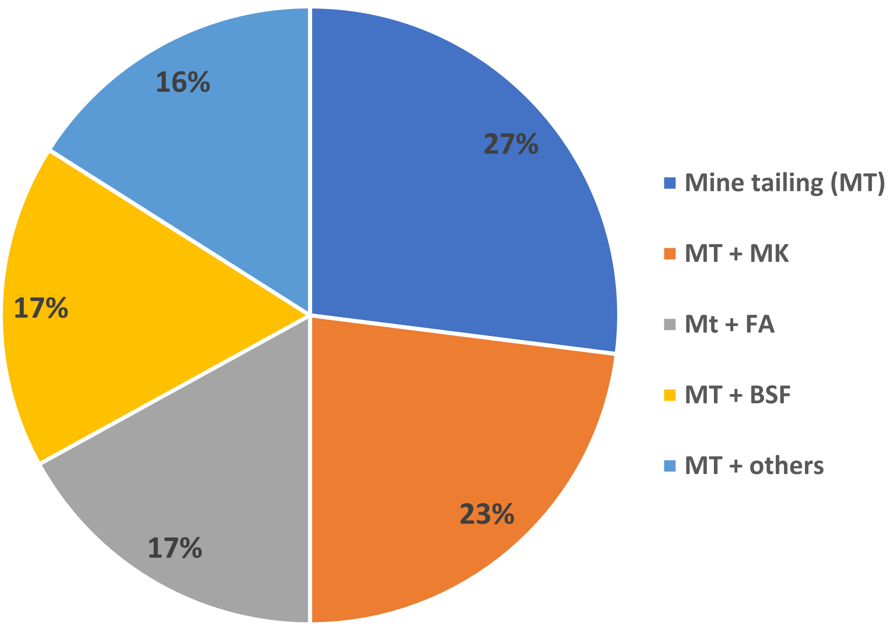


**Fig. 5.** Source of GP precursors utilized with MT to the production of MT-GPC [55].

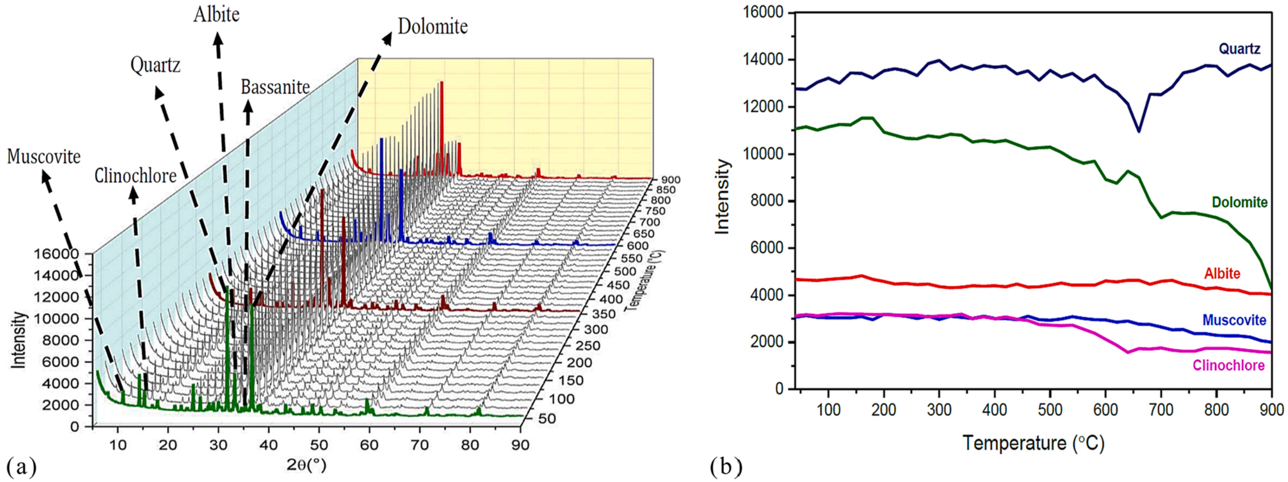


**Fig. 6.** (a) XRD analysis of MT through heat treatment; (b) Intensity variance for some main components [145].

↱processes. Mechanical activation is often performed in mills, like planetary mills, roller mills, ↱ball mills, jet mills, and agitation mills, among other forms of equipment [168–175]. In addition, mechanical activation has the potential to considerably alter both the chemical and physical ↱characteristics of MT; these impacts raise the concentration of alumino-silicate↱ ↱in alkaline sol, which in turn promotes the geopolymerisation reaction. Thermal ↱pre-treatment can be utilized in place of mechanical activation in some cases. Its formation in heating ↱raw substances to a specific temperature and causing modifications in structural, the results of which ↱are dependent on a number of characteristics like the heating rate, holding temperature and ↱duration, the environment, and the rate at which the raw substances cool [176]. ↱Mineral changes occur as a consequence of the thermal pre-treatment; in some cases, the high

**Table 5**
Compressive strength for various MT-GPC.↱.

| MT types | GP 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) | [118] |
| | | 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) | [186] |
| | | 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) | [142] |
| | – | – | SH | 35 | 0.3–5.3 (7 d) | [156] |
| | Aluminium sludge | 0–20 | SH | 95 | 11–45 (7 d) | [167] |
| | Low-Ca flash-furnace copper smelter slag | 0–100 | SH | 65–105 | 1–76 (7 d) | [189] |
| | – | – | n.m. | n.m. | 3–33.6 (7 d) | [180, 188] |
| | FA | 0–100 | SH | 60 | 3–7 (2 d) | [190] |
| | | 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 | MK | 50, 62 | SS & SH | 20–50 | 14–32 (28 d) | [139] |
| | BFS | 0, 50, 62 | SS & SH | 20–50 | 14–15.4 (28 d) | |
| Garnet | MK | 0–100 | SS & SH | 20–50 | 1–45 (3 d) | [151] |
| Gold | FA | 0–50 | – | – | 1–12 (3 d) | [181] |
| | Basic oxygen furnace slag | 0–50 | – | – | 1–22 (3 d) | |
| | BFS | 10, 25 | SS, SH & CH | Ambient | 6–19 (28 d) | [139, 191] |
| Iron | – | – | SH | 100 | 18–112.8 (7 d) | [124] |
| | Glass wool residue | 10–30 | SH | 100 | 19–41.9 (7 d) | |
| | FA | 70, 80, 90, 100 | n.m. | n.m. | 42–49 (28 d) | [126, 192] |
| | – | – | SS | 80 | 1–34 (3 d) | [12] |
| | | – | SS | 80 | 50.5 (7 d) | |
| Kaolinite | – | – | – | 40 & Ambient | 12–15 (7 d) | [150] |
| Phosphate | MK | 30, 40 | SS & SH | 60 & Ambient | 24–39.94 (28 d) | [93] |
| | – | – | | | 4 (7 d) | [3] |
| | | – | – | 40 & Ambient | 4–7 (7 d) | [150] |
| | MK | 50, 100 | SS & SH | 60, 85 & Ambient | 12.8–53 (14 d) | [76,93] |
| | FA | 50, 100 | SS & SH | 60, 85 & Ambient | 13.3–62 (14 d) | |
| Quartz | MK | 700, 80, 90 | KH & KS | 20 | 12.8–15 (1 d) | [153] |
| | | 70, 80, 90 | KH & KS | 20 | 16–18.5 (7 d) | |
| | | 70, 80, 90 | KH & KS | 20 | 17–20 (28 d) | |
| Sphalerite | MK | 0, 10, 20,30, 40, 50 | SS | 60 & Ambient | 2–15 (7 d) | [154] |
| Tungsten | WG | 0, 20, 30, 40 | SS & SH | 20–80 & 20 | 0.6–29 (1 d) | [193] |
| | | 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 | MK | 30 | SH | Ambient | 2.6–29 (7 d) | [148] |
| | | N.M. | SS | Ambient | 8.6–22.5 (7 d) | [134] |
| | | N.M. | SS | Ambient | 8.6–25 (14 d) | |
| | | 0, 10, 20, 30, 40 | SH | 20 & Ambient | 10.8–55.6 (7 d) | [194] |
| Zinc | MK | 0, 10, 20, 30, 40, 50 | SS | 60 & Ambient | 1.2–30.2 (7 d) | [185] |

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

temperature ↱might surpass the breakdown temperature of the minerals being treated. The removal of diaspore ↱and kaolinite was observed by Ye, Zhang and Shi [118] after calcining bauxite tailings at 800 °C for 1 h, which increased the interaction of the MT during geopolymerisation.↱ As shown in Fig. 6, after thermal treatment at almost 600 °C, Kiventerä, Sreenivasan, Cheeseman, Kinnunen and Illikainen [145] noted a decrease in the dolomite peak shown by gold tailings. When heated over 400 °C, basanite transformed into anhydride. On the other hand, the quartz amount remained stable until 650 °C, when it declined slightly. ↱.

As shown in Tables 5 and 6, there are a variety of parameters that impact the mechanical ↱characteristics, compressive strength, and flexural strength of various forms of MT that ↱are employed as a GP source. They are frequently combined with other alumina-silicate ↱source substances, like FA, BFS, MK, and so on, for making ↱GPs. According to the results of these tables, the compressive and flexural strengths of ↱all MT-GPC varied considerably, primarily as a result of the utilization of various forms ↱of MT, various forms of additional alumina-silicate resource substances, utilization of various forms of ↱AAs, a diverse array of AA/binder proportions, temperature, curing duration, ↱and humidity.

The curing temperature (CT) of MT-GPC has a substantial impact on the mechanical and microstructure ↱characteristics and of the polymers. Tian, Xu, Song, Rao and Xia [157] studied the ↱impact of CT on the characteristics of copper tailing-based geopolymers. When ↱the CT was somewhat enhanced (22–80 °C), homogeneous dissolution of ↱alumino-silicate↱ 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 CT over 80 ↱↱°C, on the other hand, had the opposite impact. The high CTs ↱↱(between 100 and 125 ↱°C) resulted in a lowering in the amount of alkaline medium ↱present, which prevented the dissolution of silica and alumina types. ↱↱.

The compressive and flexural strengths of GP produced from copper mine ↱tailings (CMT) as resource material ↱and activated with a variety of AAs were investigated by a number of researchers. In ↱its investigation, Falah, Obenaus-Emler, Kinnunen and Illikainen [177] found that rising the amount of sodium silicate utilized, as well as ↱the curing period and CT, improved the compressive strength of CMT-GPC. The CMT-GPC, which had been activated by sodium silicate sol, was ↱baked at a moderate temperature in an oven. They also discovered that the flexural strength of ↱CMT-GPC improved in a manner similar to that found in the relates of compressive ↱strength. Similarly, in the relates of CMT-GPCs activated by hydroxide of sodium, ↱the improvement in compressive strength with a raise in molarity of sodium hydroxide has been observed in the ↱works of [79,142].

The compressive strength of a CMT-GPC activated by sodium hydroxide improved with a ↱ boost in forming pressure throughout moulding in the investigation of Ahmari and Zhang [178], 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. 7 once the water content was exceeded. They also discovered that after ↱being submerged in water, compressive strength dropped considerably. Additionally, Manjarrez and Zhang [156] demonstrated that a lowering in moisture content below 14% resulted in an ↱improvement in the compressive strength of CMT-GPC triggered by sodium hydroxide. The raise ↱in CT up to 90 ↱°C also resulted in an improvement in the compressive ↱strength of a CMT-GPC activated by sulfur dioxide [178].↱

The compressive strength of CMT-GPC is improved when extra alumina-silicate source ↱materials are added [142]. In addition, a rise in copper slag concentrations, a raise in ↱ sodium silicate/sodium hydroxide proportions up to 1.0, and a raise in the molarity of sodium hydroxide sol up to 10 molarity all lead to an ↱improvement in the compressive strength of CMT-copper slag blended geo-polymer [179,180].↱

Iron MT (IMT)-GPC is created in a similar manner to CMT-GPC, with or ↱without the incorporating of alumina-silicate source substances. In one investigation, the compressive strength ↱of an IMT-GPC activated by sodium silicate was improved with a raise in CT up to 80 ↱°C and a raise in curing period up to 7-d, after which ↱the compressive strength declined [132].↱

The GP made from gold MT (GMT) and various AAs as well as ↱extra alumina-silicate components has been the subject of a few investigations in which ↱researchers have given close attention. GMT-GPC was synthesized by Falayi [181] ↱utilizing potassium aluminate, potassium silicate, and potassium hydroxide ↱activators. The maximum compressive strength of GMT-GPC was discovered at a ↱ potassium silicate/potassium hydroxide proportion of 1.1, according to its findings. According to its findings, rising the CT from 65 to 100 ↱°C enhanced the compressive strength of potassium aluminate and potassium hydroxide-activated GMT-GPC. The

**Table 6**
Flexure strength for several MT-GPC.↱.

| MT type | GP 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) | [118] |
| | | 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) | [186] |
| | | 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) | [124] |
| | Glass wool residue | 10–30 | SH | 100 | 2.05–4.7 (7 d) | |
| Quartz | MK | 70, 80, 90 | KH & KS | 20 | 1.7–2.1 (1 d) | [153] |
| | | 70, 80, 90 | KH & KS | 20 | 2.0–2.5 (7 d) | |
| | | 70, 80, 90 | KH & KS | 20 | 2.0–2.5 (28 d) | |

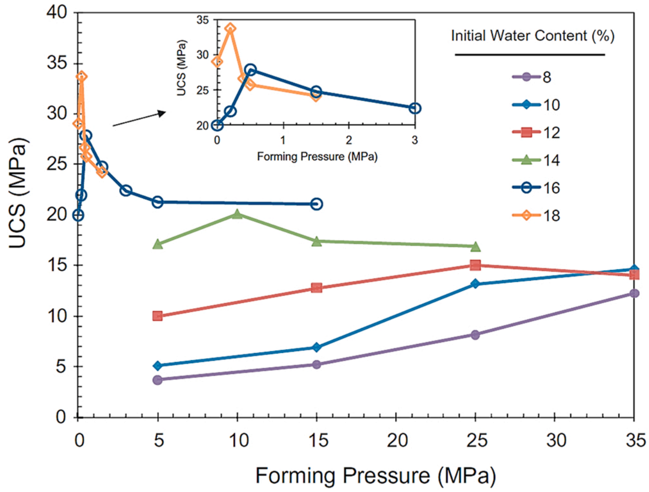


**Fig. 7.** Unconfined compressive strength (UCS) versus forming pressure for samples produced at varying water contents including 15 Molarity NaOH dosage and cured at 90 °C for 7-d [188].

researchers also discovered that the compressive ↱strength of GP activated by potassium aluminate and potassium hydroxide activators is more than ↱ that of GP ↱activated by potassium silicate and potassium hydroxide activators, even when the CT is raised to up to 100 ↱↱°C.

According to an investigation conducted by ↱↱Pardavé, Epalza, Durán and Lóvera [182], an enhancement in compressive strength of ↱GMT and alumina/kaolin mixed GP was seen when the curing period was raised. In addition, the investigation by Kiventerä, Yliniemi, Golek, Deja, Ferreira and Illikainen [183] found that rising the slag concentrations ↱and molarities of sodium hydroxide sol resulted in an improvement in the compressive strength of GMT-↱slag/metakaolin blended GP as shown in Fig. 8 [183].↱

The investigators Solismaa, Ismailov, Karhu, Sreenivasan, Lehtonen, Kinnunen, Illikainen and Räisänen [184] also discovered that the incorporating of 25% MK ↱enhanced the compressive strength of MT-GPC produced with a sodium hydroxide activator. ↱They also found a considerable improvement in compressive strength with a raise in CT up to 65 ↱°C, with a considerable lowering in compressive strength at 85 ↱↱°C, as previously reported. Concerning the compressive and flexural strengths of ↱GP, no set optimal quartz MT (QMT) quantity has been seen for any of the curing times tested. The ↱drying shrinkage and porosity of GP are both lessened when the QMT content is 30 ↱% or higher, however. In contrast to other MT-GPC, the compressive ↱strength of zinc tailings and MK-GPC improves with a raise in the amount of ↱MT present [154,185]. Wei, Zhang and Bao [134], Jiao, Zhang and Chen [149] both published investigations ↱on vanadium MT-geopolymer including FA and MK, respectively, as additional raw materials of alumina-silicate in addition to vanadium MT.

Ye, Zhang and Shi [186] discovered an enhancement in compressive strength and flexural strength advance with an ↱addition in time at low-CT in an unknown MT-GPC comprising 30% slag in an undisclosed MT-GPC. This demonstrates that the compressive and

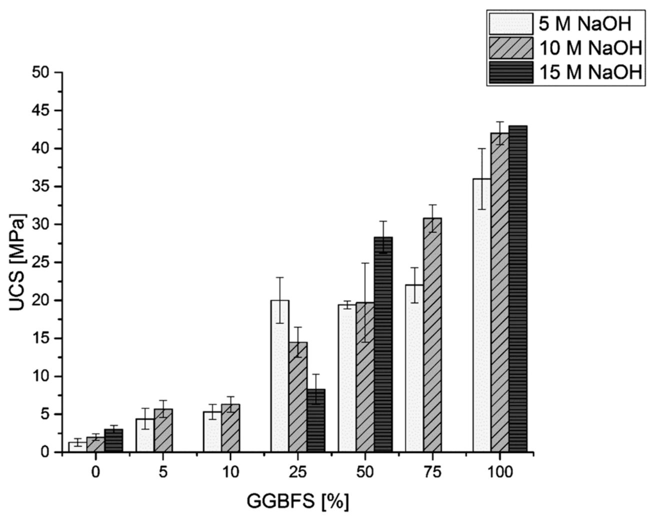


**Fig. 8.** Unconfined compressive strength (UCS) ↱of bricks with varying GGBFS- and NaOH– content after 28-d [183].

flexural strengths of concrete cured at low temperatures are lesser than those of concrete ‏cured at a typical temperature of 22 ‏°C. One possibility for the poor compressive ‏and flexural strengths of such GP might be because of the sluggish GP reaction ‏occurring at such low temperatures. ‏.

By incorporating reinforcing fibers into MT-GPC, it is possible to improve its ‏mechanical characteristics. By examining the specimen of GP matrix made from non-heat-‏treated phosphate MT, Haddaji, Majdoubi, Mansouri, Tamraoui, Manoun, Oumam and Hannache [187] demonstrated that the incorporating 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. 1% synthetic fibers produced the best ‏mechanical qualities, according to the research. When flexural strength was improved relative to ‏the original MT-GPC matrix, the percentage increase was 277% for ‏polypropylene fibers and 27% for glass fibers, respectively.‏

## 6. Durability properties

Only a few research have examined the long-term durability of MT-GPC. With ‏the help of Caballero, Sánchez and Ríos [195] the gold MT-geopolymer was subjected to sulfate and acid ‏sol as well as high temperatures. According to its findings, the rate of loss in ‏compressive strength with immersing time in sulfuric and nitric acid sol is fairly ‏comparable in GMT-GPCs when compared to a reference ‏ cementitious composite. Similar outcomes are found in magnesium and sodium sulfate sol, as well as ‏when the sol is subjected to high temperatures, as well. Ahmari and Zhang [178] ‏discovered that copper MT-GPC submerged for 120-d in aqueous sol with ‏pH values ranging between 4 and 7 had a substantial drop (by 58–79% compared to reference ‏specimens) in its plain compressive strength. The high initial Si/Al proportion and partial ‏geopolymerisation of the MT, according to the scientists, were responsible for this result. ‏Water absorption and weight loss, on the other hand, were quite minor and had lower values in comparison to the OPC-based binding agent.‏ Another study by Ahmari and Zhang [79] shown that introducing cement kiln dust can improve durability and unconfined compressive strength. The beneficial impact of cement kiln dust was connected with improved alumino-silicate dissolving, production of calcium carbonate, and calcium incorporation into the geopolymer system. Falayi [181] demonstrated that activating with potassium aluminate results in a better resistance of GPs to alternate wetting-drying than potassium silicate. In all situations, the UCS values declined by more than threefold after ten wet and dry cycles, complicating the deployment of such composites in regions with a high cyclicity of wet and dry periods and necessitating the investigation for strategies to mitigate these detrimental impacts.

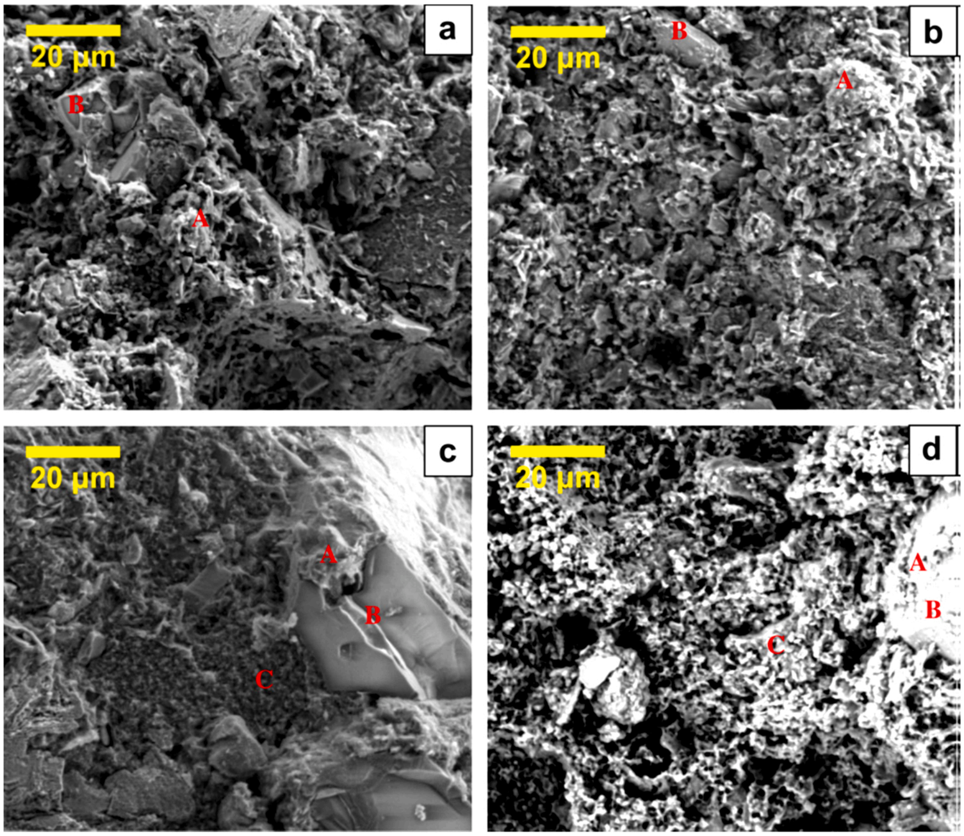


**Fig. 9.** SEM image of GP brick samples made at 15 molarity NaOH, 16% water content, and cured for 7-d at 90 C: (a) 0% CKD, (b) 5% CKD, (c) 10% CKD, and (d) 10% CKD and after immersion in water for 7-d. (A and C indicate the binder stage, while B indicates the unreacted stage) [79].

The utilization of tailings to substitute natural aggregates (gravel or sand) in GP concretes, ↱either partially or completely, might lead to an upsurge in the water absorption and porosity of ↱the latter [160]. In turn, this can make these substances more vulnerable to chemical assault, which ↱can have a detrimental impact on their overall durability. Further investigation in this field is needed because of a lack of understanding about these and other characteristics of the durability of MT-GPC, which suggests a need for future research in this area. ↱.

## 7. Microstructure properties

The microstructure of geopolymerisation products; the content, structure, and proportion of the produced amorphous and crystalline phases; as well as, the existence, distribution, and size of pores, are ↱all useful factors in determining the attributes of MT-GPC. ↱.

Falah, Obenaus-Emler, Kinnunen and Illikainen [177] found out that rising the sodium silicate content of a CMT-GPC up to 30% densifies the microstructure of the material. It was also ↱discovered that, at such a concentration of sodium silicate, almost the whole GP is changed into fused ↱rectangular prisms, which indicates a full transition to high alkaline conditions. ↱↱Manjarrez, Nikvar-Hassani, Shadnia and Zhang [142] have found that when copper slag is introduced to its GP, the density of the ↱GP increases as measured by SEM image analysis. Its ↱findings that copper slag increased the width of the amorphous peak in the XRD of CMT-GPC, while the crystalline peak in the CMT stayed the same after geopolymerisation are ↱consistent with the SEM findings. ↱.

The XRD examination findings of its 28-day-cured GP also reveal a lowering in the ↱ferocity of crystalline peaks, suggesting that the dissolution of the Al and Si components in the ↱geopolymerisation process has progressed farther than previously thought. SEM pictures of ↱CMT-GPC obtained in the work by Ren, Zhang, Ramey, Waterman and Ormsby [167] show that raised aluminium ↱sludge levels lead to the development of more GP gels. In addition, they verified ↱that there were no unreacted particles at an aluminium ↱sludge concentration of 21% in their experiment. ↱According to Ahmari and Zhang [79] investigation, as shown in Fig. 9, the improved microstructure of CMT-GPC is because of the incorporating of cement kiln dust (CKD), which results in the formation of additional ↱GP gels, which is evident from a raised Si/Al proportion.

Because of the incorporating of IMT to FA-GPC, Duan et al. demonstrated that the ↱GP became denser by producing more C–S–H [121,126]. They ↱also examined the microstructure of its GP after it had been exposed to high ↱temperatures and found that it had suffered no substantial damage to its microstructure after ↱seven heating cycles at 200 ↱°C. After exposure to 800 ↱°C, increased ↱numbers of pores and fractures were seen in FA-GPC that did not include IMT, ↱however, this was not the case in FA-GPC that had 20% IMT after the same ↱temperature.↱

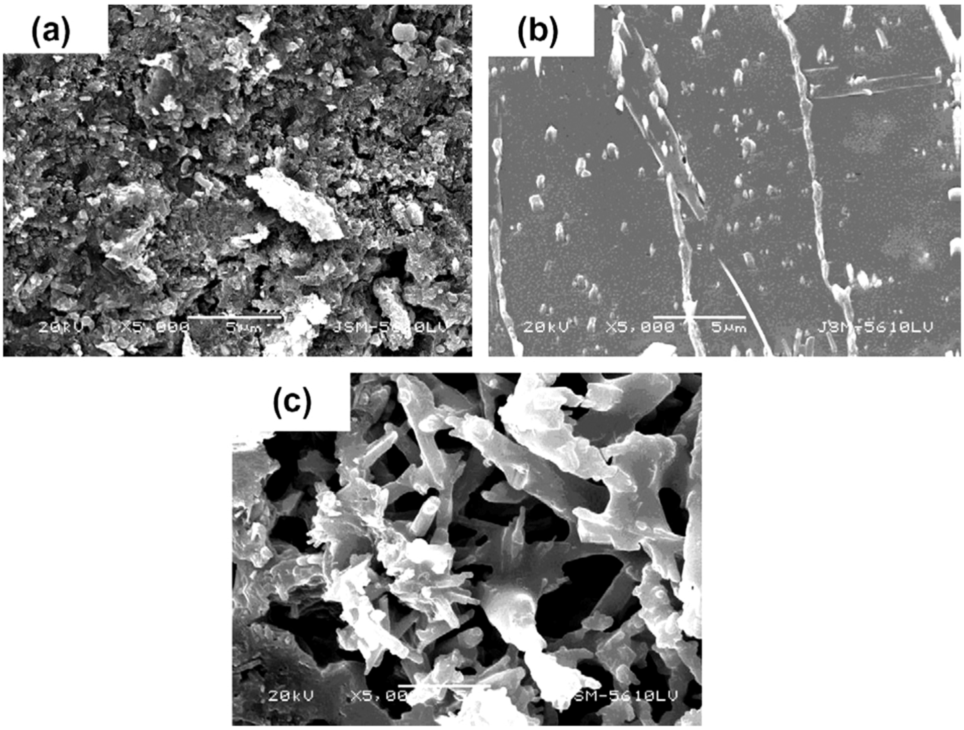


**Fig. 10.** SEM microanalysis of the GP specimen: (a) ambient temperature; (b) at 900 °C; and (c) at 1050 °C [149].

## 8. Thermal properties

As previously stated, GPs, in contrast to OPC binders, are ↱recognized by high thermal stability and the ability to retain strength even after being ↱subjected to high temperatures [196,197]. This is because of the unique characteristics of its structure, ↱which is formed by branched AlO4 and SiO4 tetrahedral frameworks [196,197]. In addition to the ↱technique of composition and curing of the AA, the kind of aggregate or alumino-silicate↱ ↱precursor utilized in the production of GPs plays a main function in the ↱ advance of the thermal characteristics of GPs. It should be noted that, when tailings ↱are included in GPs, a careful investigation of the physical evolution and ↱performance of these substances under cyclic and constant temperature exposure is required in order to ↱determine the probability of its application as thermal insulation and fire-resistant materials. ↱.

Ye, Zhang and Shi [119] investigated the impact of raised temperatures on the ↱characteristics of a GP made from bauxite tailings and slag. They discovered that ↱the compressive strength of GP is somewhat boosted after exposure to 200 ↱°C↱, but that it rapidly reductions after exposure to 600 ↱°C. However, the drop in ↱compressive strength was substantial between 600 and 1000 ↱°C, subsequent to a little ↱gain in compressive strength at 1200 ↱°C. It was discovered that the ↱production of ceramic phases, particularly anorthite ($CaAl_2(SiO_4)_2$), was associated with the ↱improvement in strength and that this was clarified by self-healing and densification caused by ↱sintering. The noticed drop in compressive strength at temperatures reach 800 ↱°C is ↱because of the dissolution of the amorphous stage as well as an extra thermal mismatch between the ↱contracting gels throughout the contracting process. Physical harm in the form of surface ↱cracking of samples also coincides well with the findings of the compression experiment, which show ↱that no severe cracking can be visible on the sample reach to 400 ↱°C. However, the ↱ferocity of cracking increases with a rise in high temperature, starting at 600 ↱°C↱ and progressing to severe cracking at 1200 ↱°C. The pores width of its ↱GP's micro-pores is likewise broadened as the temperature of the GP is raised to ↱higher levels. ↱.

According to Jiao, Zhang and Chen [149], the strength gain of MT-GPC when subjected to ↱high temperatures has also been reported. As a result of sintering, the GPs produced by ↱the AA of vanadium tailings with high silica content demonstrated an improvement in ↱compressive strength at temperatures above 900 ↱°C. This was accompanying a ↱lowering in the content of unreacted alumino-silicate↱ precursor particles and the development of a ↱denser microstructure by means of sintering as shown in Fig. 10. Heating to 1000 ↱°C, on ↱the other hand, lead to a considerable lowering in bulk density and strength, as well as an ↱increase in fracture and the porosity of GPs as shown in Fig. 11. The volume expansion and acute thermal ↱incompatibility were shown to be responsible for this phenomenon. ↱.

## 9. Applications

Utilizing MT as a commodity to make GP is a good idea for making it more ↱widely utilized. A lot of articles have looked into how MT-GPC could be ↱ utilized. GPs are a good nominee for recycling MW, making sustainable construction, and building materials, stabilizing substances and backfilling mine putty to keep toxic ↱elements out. This method not only lessens the carbon footprint of OPC but also avoids the ecological damage resulting from the accumulation of MW. Table 7 shows the various ways MT can be utilized as source substances or ↱aggregates for GP materials based on previous work.↱

## 10. Conclusions

Key annotations for this paper review are as follows:

1. GPs seem to be attractive options for recovering MWs and generating sustainable ↱ building and construction materials, mine paste backfill, and stabilizing materials for hazardous ↱element immobilization, according to the investigation. This strategy not only provides for a ↱lowering in the carbon footprint associated with typical cementitious materials but also ↱avoids the substantial ecological contamination produced by MW buildup. ↱

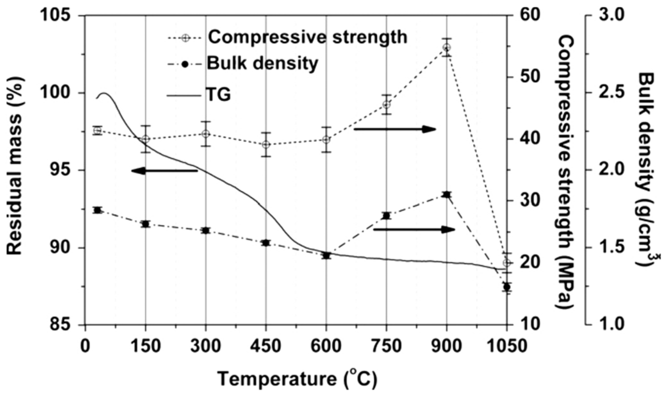


**Fig. 11.** Compressive strength, residual mass, and bulk density of the GP specimen at high temperatures [149].

**Table 7**
Various Applications of MT-GPC.

| MT types | GP blend types | Remarks | Applications | Refs. |
|---|---|---|---|---|
| Copper | FA-GPC | Microstructures that are the same across the board | Binder materials | [157] |
| | CKD-GPC | high compressive strength; high durability | Bricks | [79, 178] |
| | – | Stability in chemical terms | | [143] |
| | – | High compressive strength | | [179, 180] |
| | – | High mechanical characteristics | Road-construction materials | [156] |
| | low- calcium slag-GPC | High mechanical characteristics | | [142] |
| Gold | $Al_2O_3$-GPC | High adsorption capacity because of porous structure | Pb2 + adsorbent from aqueous sol | [90,91] |
| | $Al_2O_3$-GPC | High adsorption capacity because of porous structure | | |
| gold | BFS-GPC & MK-GPC | High mechanical characteristics | Lightweight aggregates | [183] |
| | FA-GPC | Low water absorption and loose bulk density; large void volume | | [3] |
| Iron | FA-GPC | compressive strength and Improved setting time | Binder materials | [137] |
| | FA-GPC | Low porosity and microcracking; good thermal resistance | | [126] |
| | Glass wool residue-GPC | High compressive strength and flexural strength | | [124] |
| | BFS-GPC & FA-GPC | High compressive and hardness strength; homogeneous structure | Bricks | [198] |
| | FA-GPC | High adsorption capability; porous structure | $Cu^{2+}$ adsorbent from water | [126] |
| | – | Low electrical resistance; high compressive strength, low water absorption | Bricks | [132] |
| | – | High compressive strength | Backfills for building foundations; road-bed material, | [152] |
| Phosphate | – | High compressive strength | Binder materials | [93] |
| | FA-GPC & MK-GPC | density and Mechanical characteristics are both high | | |
| Silica-rich vanadium | FA-GPC | Temperature stability across a wide range | Fire-resistant materials | [149] |
| Sphalerite | MK-GPC | Toxic components have a high immobilization ability | $Pb^{2+}$ immobilization | [185] |

2. Several aspects impact how well MT-GPC functions 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 MT.
3. MT are often composed of a highly crystalline matrix, which results in minimal interaction throughout geopolymerisation and, as a consequence, a product with low mechanical characterizes. Incorporating extra elements with increased interaction into MT-GPC may efficiently tune and enhance the characteristics of the GPs. Furthermore, since the majority of the additives utilized for this function are industrial by-products, its usage has the additional benefit of lessening the amount of waste produced. When compared to low-Ca-comprising additions, high Ca-comprising elements have a higher favorable impact on the GP'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 dense.
4. Supplementary materials, particularly those containing a high calcium content, tend to be more efficient at developing the resulting GP characteristics.
5. The minerals that form MT 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 GP's alumino-silicate framework. The alkaline reactivity of MT is often low, which is the most advantageous characteristic when MT is utilized in GPs.
6. Pre-treatment of MT can be utilized to boost its interaction, and it has been done effectively. This can be accomplished by the utilization of mechanical, thermo-chemical, and thermal activation techniques that increase the specific surface area of the MT components and transform them into amorphous and soluble states. Among the most successful pre-treatment methods for industrial solid waste, mechanical activation is one of the most effective; for instance, grinding may increase the possible interaction of cement-based materials. The energy needs for wet-grinding and dry-grinding are 1.65 kW, respectively, to get rid of the product itself. In light of the fact that mineral comminution accounts for approximately 4–5% of all global electricity consumption, this energy consumption is considerable. Furthermore, the impact of mechanical pre-treatment on the compressive strength of the last GP is less clear compared to the impact of adding supplementary materials.
7. The increase in interaction after pre-treatment enables a high-rate of geopolymerisation at an initial phase and higher mechanical characteristics of the cured materials. In addition, the high silica concentration of MT raises the molar proportion of $SiO_2$/$Al_2O_3$ in MT-GPC, impairing the process of geopolymerisation. A sol to this difficulty can be found by including additional precursors, like MK or scattered aluminium oxide, into the mix. As a result, a preliminary classification of tailings based on the characteristics of their mineralogical and chemical compositions is recommended.
8. According to the results of the references study, dehydrated tailings are utilized for the manufacturing of GPs more frequently than other forms of tailings. Dehydrated tailings are created either by dry tailing operations or by basically drying the MT paste or slurry subsequently grinding. When employing MT-GPC, it is crucial to consider not only its mineralogical, physical, and

chemical characteristics, but also the possibility of the presence of numerous pollutants, like processing liquids, heavy metals, and other contaminants in its composition. However, the concerns of movement of these pollutants under the impact of leaching and other processes, additionally to its impact on the attributes of final components derived from MT-GPC, have received comparatively little attention in the scientific literature. Furthermore, natural radionuclides can be found in MT in amounts that exceed the radiological safety criteria, which should be considered while employing MT in GPs.

9. No classification strategy for MT is in place that is based on its interaction. Recent research findings, like employing the topological technique to assess glass interaction, can be utilized to categorize and classify these materials, hence encouraging its usage in geopolymerisation applications.

## 11. Recommendations

The following are the main recommendations for future investigations:

1. Incorporating extra elements with increased interaction into MT-GPC may efficiently tune and enhance the characteristics of the GPs. Therefore, further investigation is recommended in this regard.
2. The high silica concentration of MT raises the molar proportion of SiO2/Al2O3 in MT-GPC, impairing the process of geopolymerisation. A sol to this difficulty can be found by including additional precursors, like MK or scattered aluminium oxide, into the mix. As a result, a preliminary classification of tailings based on the characteristics of their mineralogical and chemical compositions is recommended.
3. When employing MT-GPC, it is crucial to consider not only its mineralogical, physical, and chemical characteristics, but also the possibility of the presence of numerous pollutants, like processing liquids, heavy metals, and other contaminants in its composition. However, the concerns of movement of these pollutants under the impact of leaching and other processes, additionally to its impact on the attributes of final components derived from MT-GPC, have received comparatively little attention in the scientific literature. Furthermore, natural radionuclides can be found in MT in amounts that exceed the radiological safety criteria, which should be considered while employing MT in GPs.
4. Because of the deficiencies in past decades' preparation processes, MT accumulating in landfills or tailing piles might contain considerable amounts of unrecoverable precious metals, and as a result, can serve as a viable technogenic raw material for recycling. If the utilization of metal-comprising tailings is not supplemented by the mining of beneficial components from them, it may be deemed economically unjustifiable. As a result, the concerns of neutralization of contaminants present in tailings and further mining of useful components from MT for its long-term usage in GPs need to be addressed.
5. Because of the low interaction of native metal trichlorides, the presence of beneficial components ingrained in the minerals initially processed, and the risk of toxic contamination by leaching components, utilizing tailings for GP preparation is prohibitively expensive and time-consuming from an economic and production standpoint. Aspects like the geographic closeness of the mining and processing enterprises to the MT customers as well as the regions where finished GP products are consumed should be taken into consideration when conducting a feasibility study for its application in GP composites.
6. The interactions of the precursors' metal components in alkaline conditions affect the structure and characteristics of GP's alumino-silicate framework. Therefore, further investigation is recommended in this regard.
7. Pre-treatment of MT can be utilized to boost its interaction. Therefore, further investigation is recommended in this regard.

## Declaration of Competing Interest

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

## References


[1] L. Dong, X. Tong, X. Li, J. Zhou, S. Wang, B. Liu, Some developments and new insights of environmental problems and deep mining strategy for cleaner production in mines, J. Clean. Prod. 210 (2019) 1562–1578.

[2] M. Nurcholis, D.F. Yudiantoro, D. Haryanto, A. Mirzam, Heavy metals distribution in the artisanal gold mining area in Wonogiri, Indones. J. Geogr. 49 (2) (2017) 133–144.

[3] N.J. Vickers, Animal communication: when i'm calling you, will you answer too? Curr. Biol. 27 (14) (2017) R713–R715.

[4] W.-h Zhou, Y.-t Wang, Z.-h Lian, T.-t Yang, Q.-w Zeng, S.-w Feng, Z. Fang, W.-s Shu, L.-n Huang, Z.-h Ye, B. Liao, J.-t Li, Revegetation approach and plant identity unequally affect structure, ecological network and function of soil microbial community in a highly acidified mine tailings pond, Sci. Total Environ. 744 (2020), 140793.

[5] A. Vasile, A.R. Milăşan, A.E. Andrei, R.N. Turcu, M.F. Drăgoescu, S. Axinte, M. Mihaly, An integrated value chain to iron-containing mine tailings capitalization by a combined process of magnetic separation, microwave digestion and microemulsion – assisted extraction, Process Saf. Environ. Prot. 154 (2021) 118–130.

[6] N. Min, J. Yao, M. Amde, L. Wu, G. Sunahara, H. Li, Y. Chen, J. Liu, V.G. Mihucz, Accelerated solvent extraction combined with GC–MS: a convenient technique for the determination and compound-specific stable isotope analysis of phthalates in mine tailings, Microchem. J. 153 (2020), 104366.

[7] D. Komljenovic, L. Stojanovic, V. Malbasic, A. Lukic, A resilience-based approach in managing the closure and abandonment of large mine tailing ponds, Int. J. Min. Sci. Technol. 30 (5) (2020) 737–746.

[8] A.M. Salam, B. Örmeci, P.H. Simms, Determination of optimum polymer dosage for dewatering of oil sands tailings using torque rheology, J. Pet. Sci. Eng. 197 (2021), 107986.

[9] Z. Li, L. Wang, G. Ma, Chapter 8 - Method for the enhancement of buildability and bending resistance of three-dimensional-printable tailing mortar, in: J. G. Sanjayan, A. Nazari, B. Nematollahi (Eds.), 3D Concrete Printing Technology, Butterworth-Heinemann, 2019, pp. 161–180.

[10] W. Hu, C.L. Xin, Y. Li, Y.S. Zheng, T.W.J. van Asch, M. McSaveney, Instrumented flume tests on the failure and fluidization of tailings dams induced by rainfall infiltration, Eng. Geol. 294 (2021), 106401.
[11] J.E. Galán, The benefits are at the tail: uncovering the impact of macroprudential policy on growth-at-risk, J. Financ. Stab. (2020), 100831.
[12] L.S. Passos, K.G. Gnocchi, T.M. Pereira, G.C. Coppo, D.S. Cabral, L.C. Gomes, Is the Doce River elutriate or its water toxic to Astyanax lacustris (Teleostei: Characidae) three years after the Samarco mining dam collapse? Sci. Total Environ. 736 (2020), 139644.
[13] E.A. Deliyanni, G.Z. Kyzas, K.S. Triantafyllidis, K.A. Matis, Activated carbons for the removal of heavy metal ions: a systematic review of recent literature focused on lead and arsenic ions, Open Chem. 13 (1) (2015).
[14] J. Schäfer, A. Coynel, G. Blanc, Impact of metallurgy tailings in a major European fluvial-estuarine system: trajectories and resilience over seven decades, Sci. Total Environ. 805 (2022), 150195.
[15] Gd.S. Santos, E.E.C. Silva, G.F. Barroso, V.M.D. Pasa, E.M. Eskinazi-Sant'Anna, Do metals differentiate zooplankton communities in shallow and deep lakes affected by mining tailings? The case of the Fundão dam failure (Brazil), Sci. Total Environ. 806 (2022), 150493.
[16] H.M. Queiroz, S.C. Ying, M. Abernathy, D. Barcellos, F.A. Gabriel, X.L. Otero, G.N. Nóbrega, A.F. Bernardino, T.O. Ferreira, Manganese: the overlooked contaminant in the world largest mine tailings dam collapse, Environ. Int. 146 (2021), 106284.
[17] M. Perrett, B. Sivarajah, C.L. Cheney, J.B. Korosi, L. Kimpe, J.M. Blais, J.P. Smol, Impacts on aquatic biota from salinization and metalloid contamination by gold mine tailings in sub-Arctic lakes, Environ. Pollut. 278 (2021), 116815.
[18] C.E.T. Parente, A.S. Lino, G.O. Carvalho, A.C. Pizzochero, C.E. Azevedo-Silva, M.O. Freitas, C. Teixeira, R.L. Moura, V.J.M. Ferreira Filho, O. Malm, First year after the Brumadinho tailings' dam collapse: spatial and seasonal variation of trace elements in sediments, fishes and macrophytes from the Paraopeba River, Brazil, Environ. Res. 193 (2021), 110526.
[19] V.Od Almeida, T.C.B. Pereira, Ld.S. Teodoro, M. Escobar, C.J. Ordovás, K.B. dos Santos, J. Weiler, M.R. Bogo, I.A.H. Schneider, On the effects of iron ore tailings micro/nanoparticles in embryonic and larval zebrafish (Danio rerio), Sci. Total Environ. 759 (2021), 143456.
[20] J. Csavina, J. Field, M.P. Taylor, S. Gao, A. Landázuri, E.A. Betterton, A.E. Sáez, A review on the importance of metals and metalloids in atmospheric dust and aerosol from mining operations, Sci. Total Environ. 433 (2012) 58–73.
[21] W. Zhang, J. Long, X. Zhang, W. Shen, Z. Wei, Pollution and ecological risk evaluation of heavy metals in the soil and sediment around the HTM Tailings Pond, Northeastern China, Int. J. Environ. Res. Public Health 17 (19) (2020) 7072.
[22] M. Moradi, Y. You, H. Hung, J. Li, R. Park, N. Alexandrou, S.G. Moussa, L. Jantunen, R. Robitaille, R.M. Staebler, Fugitive emissions of polycyclic aromatic compounds from an oil sands tailings pond based on fugacity and inverse dispersion flux calculations, Environ. Pollut. 269 (2021), 116115.
[23] X. Jiang, W. Liu, H. Xu, X. Cui, J. Li, J. Chen, B. Zheng, Characterizations of heavy metal contamination, microbial community, and resistance genes in a tailing of the largest copper mine in China, Environ. Pollut. 280 (2021), 116947.
[24] L. Jiang, H. Sun, T. Peng, W. Ding, B. Liu, Q. Liu, Comprehensive evaluation of environmental availability, pollution level and leaching heavy metals behavior in non-ferrous metal tailings, J. Environ. Manag. 290 (2021), 112639.
[25] T.M. Carvalho Eugênio, J. Francisco Fagundes, Q. Santos Viana, A. Pereira Vilela, R. Farinassi Mendes, Study on the feasibility of using iron ore tailing (iot) on technological properties of concrete roof tiles, Constr. Build. Mater. 279 (2021), 122484.
[26] P.L. Hageman, P.H. Briggs, A Simple Field Leach Test for Rapid Screening and Qualitative Characterization of Mine Waste Dump Material on Abandoned Mine Lands, US Dept. of the Interior, US Geological Survey, 2000.
[27] Q. Zhai, R. Liu, C. Wang, X. Wen, X. Li, W. Sun, A novel scheme for the utilization of Cu slag flotation tailings in preparing internal electrolysis materials to degrade printing and dyeing wastewater, J. Hazard. Mater. 424 (2022), 127537.
[28] T.A.H. Nguyen, Y. Liu, S. Wu, L. Huang, Unravelling in-situ hardpan properties and functions in capping sulfidic Cu-Pb-Zn tailings and forming a duplex soil system cover, J. Hazard. Mater. 425 (2022), 127943.
[29] L.-J. Han, J.-S. Li, Q. Xue, M.-Z. Guo, P. Wang, C.S. Poon, Enzymatically induced phosphate precipitation (EIPP) for stabilization/solidification (S/S) treatment of heavy metal tailings, Constr. Build. Mater. 314 (2022), 125577.
[30] Z. Guo, X. Sun, X. Zhang, J. Qiu, H. Jiang, Y. Zhao, P. Wu, Q. Zhang, Effect of superplasticizer on rheology and thixotropy of superfine-tailings cemented paste backfill: experiment and modelling, Constr. Build. Mater. 316 (2022), 125693.
[31] W. Chen, S. Yin, G. Zhou, Z. Li, Q. Song, Copper recovery from tailings through bioleaching and further application of bioleached tailings residue: comprehensive utilization of tailings, J. Clean. Prod. 332 (2022), 130129.
[32] S. Dudka, D.C. Adriano, Environmental impacts of metal ore mining and processing: a review, J. Environ. Qual. 26 (3) (1997) 590–602.
[33] X.-h Zhu, B.-f Sun, M. Luo, J. Yu, Y.-d Zhang, H.-q Xu, H. Luo, Bloom helicase explicitly unwinds 3′-tailed G4DNA structure in prostate cancer cells, Int. J. Biol. Macromol. 180 (2021) 578–589.
[34] A. Ray, P.P. Mehta, Cysteine residues in the C-terminal tail of connexin32 regulate its trafficking, Cell. Signal. 85 (2021), 110063.
[35] L. Pinet, Y.-H. Wang, C. Deville, E. Lescop, F. Guerlesquin, A. Badache, F. Bontems, N. Morellet, D. Durand, N. Assrir, C. van Heijenoort, Structural and dynamic characterization of the C-terminal tail of ErbB2: Disordered but not random, Biophys. J. 120 (10) (2021) 1869–1882.
[36] T. Nakamura, T. Nakade, K. Yamada, Y. Sato, H. Harashima, The hydrophobic tail of a pH-sensitive cationic lipid influences siRNA transfection activity and toxicity in human NK cell lines, Int. J. Pharm. 609 (2021), 121140.
[37] H. Li, C.D. Sibley, Y. Kharel, T. Huang, A.M. Brown, L.G. Wonilowicz, D.R. Bevan, K.R. Lynch, W.L. Santos, Lipophilic tail modifications of 2-(hydroxymethyl) pyrrolidine scaffold reveal dual sphingosine kinase 1 and 2 inhibitors, Bioorg. Med. Chem. 30 (2021), 115941.
[38] H. Kawai, K. Yazama, Y. Yanai, R. Kamitsubo, H. Kamiya, Gene correction by 5′-tailed duplexes with short editor oligodeoxyribonucleotides, J. Biosci. Bioeng. 132 (6) (2021) 552–559.
[39] R. Augustine, S. Uthaman, N. Kalva, K.H. Eom, K.M. Huh, S. Pillarisetti, I.-K. Park, I. Kim, Two-tailed tadpole-shaped synthetic polymer polypeptide bioconjugate nanomicelles for enhanced chemo-photothermal therapy, Polymer 230 (2021), 124061.
[40] H.T. Abdel-Mohsen, A.M. El Kerdawy, M.A. Omar, A. Petreni, R.M. Allam, H.I. El Diwani, C.T. Supuran, Application of the dual-tail approach for the design and synthesis of novel Thiopyrimidine–Benzenesulfonamide hybrids as selective carbonic anhydrase inhibitors, Eur. J. Med. Chem. 228 (2022), 114004.
[41] S.B. Magle, K.R. Crooks, Interactions between black-tailed prairie dogs (Cynomys ludovicianus) and vegetation in habitat fragmented by urbanization, J. Arid Environ. 72 (3) (2008) 238–246.
[42] M. Rico, G. Benito, A. Salgueiro, A. Díez-Herrero, H. Pereira, Reported tailings dam failures: a review of the European incidents in the worldwide context, J. Hazard. Mater. 152 (2) (2008) 846–852.
[43] C.M. Longhini, S.K. Rodrigues, E.S. Costa, C.A. da Silva, R.C. Cagnin, M. Gripp, B.D.C. Lehrback, G.N. Mill, E.M.C. de Oliveira, Cd.C.M. Hermogenes, D.G. F. Rodrigues, A.M. David, K.C. Gramlich, Rd.C. Bisi Júnior, A.A.P. Gomes, J.P. da Silva Filho, J.F. Almeida, K.F. de Souza, W.A.R. Luz Junior, L.M.B. Poleze, R. R. Barros, D. Rigo, R.D. Ghisolfi, R.R. Neto, F. Sá, Environmental quality assessment in a marine coastal area impacted by mining tailing using a geochemical multi-index and physical approach, Sci. Total Environ. 803 (2022), 149883.
[44] J. Lana-Costa, M.M. da Silva, A.O. Martins, J.C. Guarnier, Rd.O. Silva Junior, D.M. Silva, A. Nunes-Nesi, W.L. Araújo, Biochemical and physiological aspects of restinga herbaceous plants tolerance to iron ore tailing plume along the coastal region of Espírito Santo-Brazil, Environ. Exp. Bot. 191 (2021), 104618.
[45] K. Islam, S. Murakami, Global-scale impact analysis of mine tailings dam failures: 1915–2020, Glob. Environ. Change 70 (2021), 102361.
[46] E.B. Duarte, M.A. Neves, F.B. de Oliveira, M.E. Martins, C.H.R. de Oliveira, D.L. Burak, M.T.D.A. Orlando, C.V.G.T. Rangel, Trace metals in Rio Doce sediments before and after the collapse of the Fundão iron ore tailing dam, Southeastern Brazil, Chemosphere 262 (2021), 127879.
[47] C. dos Santos Vergilio, D. Lacerda, T. da Silva Souza, B.C.V. de Oliveira, V.S. Fioresi, V.V. de Souza, G. da Rocha Rodrigues, M.K. de Araujo Moreira Barbosa, E. Sartori, T.P. Rangel, D.Q.R. de Almeida, M.G. de Almeida, F. Thompson, C.E. de Rezende, Immediate and long-term impacts of one of the worst mining tailing dam failure worldwide (Bento Rodrigues, Minas Gerais, Brazil), Sci. Total Environ. 756 (2021), 143697.
[48] A.C. Cavalheiro Paulelli, C.A. Cesila, P.P. Devóz, S. Ruella de Oliveira, J.P. Bianchi Ximenez, Wd.R. Pedreira Filho, F. Barbosa Jr., Fundão tailings dam failure in Brazil: evidence of a population exposed to high levels of Al, As, Hg, and Ni after a human biomonitoring study, Environ. Res. 205 (2022), 112524.
[49] R.L. Burritt, K.L. Christ, Full cost accounting: a missing consideration in global tailings dam management, J. Clean. Prod. 321 (2021), 129016.

[50] C. Zhang, X. Wang, Z. Hu, Q. Wu, H. Zhu, J. Lu, Long-term performance of silane coupling agent/metakaolin based geopolymer, J. Build. Eng. 36 (2021), 102091.

[51] C. Rodrigue Kaze, A. Adesina, G. Laure Lecomte-Nana, J.V. Sontia Metekong, L. Van Essa Kamga Samen, E. Kamseu, U.C. Melo, Synergetic effect of rice husk ash and quartz sand on microstructural and physical properties of laterite clay based geopolymer, J. Build. Eng. 43 (2021), 103229.

[52] K.M. Klima, K. Schollbach, H.J.H. Brouwers, Q. Yu, Enhancing the thermal performance of Class F fly ash-based geopolymer by sodalite, Constr. Build. Mater. 314 (2022), 125574.

[53] K.V.S. Gopala Krishna Sastry, P. Sahitya, A. Ravitheja, Influence of nano TiO2 on strength and durability properties of geopolymer concrete, Mater. Today Proc. 45 (2021) 1017–1025.

[54] M. Catauro, F. Barrino, S. Pacifico, S. Piccolella, I. Lancellotti, C. Leonelli, Synthesis of WEEE-based geopolymers and their cytotoxicity, Mater. Today Proc. 34 (2021) 121–124.

[55] G. Lazorenko, A. Kasprzhitskii, F. Shaikh, R. Krishna, J. Mishra, Utilization potential of mine tailings in geopolymers: part 1. Physicochemical and environmental aspects, Process Saf. Environ. Prot. (2021).

[56] P. Kinnunen, A. Ismailov, S. Solismaa, H. Sreenivasan, M.-L. Räisänen, E. Levänen, M. Illikainen, Recycling mine tailings in chemically bonded ceramics–a review, J. Clean. Prod. 174 (2018) 634–649.

[57] B. Dold, Sourcing of critical elements and industrial minerals from mine waste–the final evolutionary step back to sustainability of humankind? J. Geochem. Explor. (2020), 106638.

[58] S. Divvala, S.R. M, Early strength properties of geopolymer concrete composites: an experimental study, Mater. Today Proc. 47 (2021) 3770–3777.

[59] J. Davidovits, L. Huaman, R. Davidovits, Ancient organo-mineral geopolymer in South-American Monuments: organic matter in andesite stone. SEM and petrographic evidence, Ceram. Int. 45 (6) (2019) 7385–7389.

[60] S. Zhao, M. Xia, L. Yu, X. Huang, B. Jiao, D. Li, Optimization for the preparation of composite geopolymer using response surface methodology and its application in lead-zinc tailings solidification, Constr. Build. Mater. 266 (2021), 120969.

[61] N. Zhang, B. Tang, X. Liu, Cementitious activity of iron ore tailing and its utilization in cementitious materials, bricks and concrete, Constr. Build. Mater. 288 (2021), 123022.

[62] N. Zhang, A. Hedayat, H.G. Bolaños Sosa, N. Tupa, I. Yanqui Morales, R.S. Canahua Loza, Mechanical and fracture behaviors of compacted gold mine tailings by semi-circular bending tests and digital image correlation, Constr. Build. Mater. 306 (2021), 124841.

[63] N. Zhang, A. Hedayat, H.G. Bolaños Sosa, R.P. Huamani Bernal, N. Tupa, I. Yanqui Morales, R.S. Canahua Loza, On the incorporation of class F fly-ash to enhance the geopolymerization effects and splitting tensile strength of the gold mine tailings-based geopolymer, Constr. Build. Mater. 308 (2021), 125112.

[64] N. Zhang, A. Hedayat, H.G. Bolaños Sosa, J.J. González Cárdenas, G.E. Salas Álvarez, V.B. Ascuña Rivera, Specimen size effects on the mechanical behaviors and failure patterns of the mine tailings-based geopolymer under uniaxial compression, Constr. Build. Mater. 281 (2021), 122525.

[65] G. Xue, E. Yilmaz, G. Feng, S. Cao, Bending behavior and failure mode of cemented tailings backfill composites incorporating different fibers for sustainable construction, Constr. Build. Mater. 289 (2021), 123163.

[66] Y. Wang, Z. Li, Q. Jin, M. Zhang, Z. Zhou, High-efficiency utilization of limestone tailings: used as cementitious materials and fine aggregate to prepare karst structure filling material, Constr. Build. Mater. 316 (2022), 125841.

[67] V. Mymrin, D.E. Pedroso, C.L. Pedroso, M.A. Avanci, P.H.B. Rolim, K.Q. Carvalho, R.E. Catai, Physical-chemical processes of sustainable construction materials structure formation with iron ore processing tailings and aluminum anodizing sludge, Constr. Build. Mater. 298 (2021), 123698.

[68] X. Kong, L. Dai, Y. Wang, D. Qiao, S. Hou, S. Wang, Influence of kenaf stalk on printability and performance of 3D printed industrial tailings based geopolymer, Constr. Build. Mater. (2021), 125787.

[69] C. Ince, S. Derogar, K. Gurkaya, R.J. Ball, Properties, durability and cost efficiency of cement and hydrated lime mortars reusing copper mine tailings of Lefke-Xeros in Cyprus, Constr. Build. Mater. 268 (2021), 121070.

[70] A. Barzegar Ghazi, A. Jamshidi-Zanjani, H. Nejati, Utilization of copper mine tailings as a partial substitute for cement in concrete construction, Constr. Build. Mater. 317 (2022), 125921.

[71] A.M.T. Bagger, W. Kunther, N.M. Sigvardsen, P.E. Jensen, Screening for key material parameters affecting early-age and mechanical properties of blended cementitious binders with mine tailings, Case Stud. Constr. Mater. 15 (2021), e00608.

[72] J. Kiventerä, P. Perumal, J. Yliniemi, M. Illikainen, Mine tailings as a raw material in alkali activation: a review, Int. J. Miner. Metall. Mater. 27 (8) (2020) 1009–1020.

[73] Yliniemi Paiva, Ferreira Tiainen, Illikainen, Development and incorporation of lightweight waste-based geopolymer aggregates in mortar and concrete, Constr. Build. Mater. 131 (2017) 784–792.

[74] P. Perumal, K. Piekkari, H. Sreenivasan, P. Kinnunen, M. Illikainen, One-part geopolymers from mining residues – effect of thermal treatment on three different tailings, Miner. Eng. 144 (2019), 106026.

[75] E.M. Opiso, C.B. Tabelin, C.V. Maestre, J.P.J. Aseniero, I. Park, M. Villacorte-Tabelin, Synthesis and characterization of coal fly ash and palm oil fuel ash modified artisanal and small-scale gold mine (ASGM) tailings based geopolymer using sugar mill lime sludge as Ca-based activator, Heliyon 7 (4) (2021), e06654.

[76] S. Moukannaa, M. Loutou, M. Benzaazoua, L. Vitola, J. Alami, R. Hakkou, Recycling of phosphate mine tailings for the production of geopolymers, J. Clean. Prod. 185 (2018) 891–903.

[77] E. Arioz, O. Arioz, O.M. Kockar, Leaching of F-type fly ash based geopolymers, Procedia Eng. 42 (2012) 1114–1120.

[78] R.S. Krishna, J. Mishra, M. Zribi, F. Adeniyi, S. Saha, S. Baklouti, F.U.A. Shaikh, H.S. Gökçe, A review on developments of environmentally friendly geopolymer technology, Materialia 20 (2021), 101212.

[79] S. Ahmari, L. Zhang, Utilization of cement kiln dust (CKD) to enhance mine tailings-based geopolymer bricks, Constr. Build. Mater. 40 (2013) 1002–1011.

[80] J.S. van Deventer, J.L. Provis, P. Duxson, D.G. Brice, Chemical research and climate change as drivers in the commercial adoption of alkali activated materials, Waste Biomass Valoriz. 1 (1) (2010) 145–155.

[81] S.M. Taher, S.T. Saadullah, J.H. Haido, B.A. Tayeh, Behavior of geopolymer concrete deep beams containing waste aggregate of glass and limestone as a partial replacement of natural sand, Case Stud. Constr. Mater. 15 (2021), e00744.

[82] J.L. Provis, J.S.J. Van Deventer. Geopolymers: Structures, Processing, Properties and Industrial Applications, Elsevier, 2009.

[83] B.A. Tayeh, A.M. Zeyad, I.S. Agwa, M. Amin, Effect of elevated temperatures on mechanical properties of lightweight geopolymer concrete, Case Stud. Constr. Mater. 15 (2021), e00673.

[84] G. Lazorenko, A. Kasprzhitskii, V. Yavna, V. Mischinenko, A. Kukharskii, A. Kruglikov, A. Kolodina, G. Yalovega, Effect of pre-treatment of flax tows on mechanical properties and microstructure of natural fiber reinforced geopolymer composites, Environ. Technol. Innov. 20 (2020), 101105.

[85] G. Lazorenko, A. Kasprzhitskii, A. Kruglikov, V. Mischinenko, V. Yavna, Sustainable geopolymer composites reinforced with flax tows, Ceram. Int. 46 (8) (2020) 12870–12875.

[86] A. Hassan, M. Arif, M. Shariq, Use of geopolymer concrete for a cleaner and sustainable environment–a review of mechanical properties and microstructure, J. Clean. Prod. 223 (2019) 704–728.

[87] M. Chau-Khun, A.A. Zawawi, O. Wahid, Structural and Material Performance of Geopolymer Concrete 2018, Elsevier, 2018.

[88] S. T, K.R. P.R, S. M, S. A, J. R, A state-of-the-art on development of geopolymer concrete and its field applications, Case Stud. Constr. Mater. 16 (2022), e00812.

[89] A.M. Zeyad, H.M. Magbool, B.A. Tayeh, A.R.G. de Azevedo, A. Abutaleb, Q. Hussain, Production of geopolymer concrete by utilizing volcanic pumice dust, Case Stud. Constr. Mater. 16 (2022), e00802.

[90] F. Demir, E. Moroydor Derun, Usage of gold mine tailings based geopolymer on Cu 2+ adsorption from water, Main Group Chem. 18 (4) (2019) 467–476.

[91] F. Demir, E.M. Derun, Modelling and optimization of gold mine tailings based geopolymer by using response surface method and its application in Pb2+ removal, J. Clean. Prod. 237 (2019), 117766.

[92] A.A. Siyal, M.R. Shamsuddin, M.I. Khan, N.E. Rabat, M. Zulfiqar, Z. Man, J. Siame, K.A. Azizli, A review on geopolymers as emerging materials for the adsorption of heavy metals and dyes, J. Environ. Manag. 224 (2018) 327–339.
[93] S. Moukannaa, A. Nazari, A. Bagheri, M. Loutou, J. Sanjayan, R. Hakkou, Alkaline fused phosphate mine tailings for geopolymer mortar synthesis: thermal stability, mechanical and microstructural properties, J. Non-Cryst. Solids 511 (2019) 76–85.
[94] N. Zhang, A. Hedayat, H.G. Bolaños Sosa, N. Tupa, I. Yanqui Morales, R.S. Canahua Loza, Crack evolution in the Brazilian disks of the mine tailings-based geopolymers measured from digital image correlations: an experimental investigation considering the effects of class F fly ash additions, Ceram. Int. 47 (22) (2021) 32382–32396.
[95] A.R. de Azevedo, M. Teixeira Marvila, L. Barbosa de Oliveira, W. Macario Ferreira, H. Colorado, S. Rainho Teixeira, C. Mauricio Fontes Vieira, Circular economy and durability in geopolymers ceramics pieces obtained from glass polishing waste, Int. J. Appl. Ceram. Technol. (2021).
[96] N. Ouffa, M. Benzaazoua, T. Belem, R. Trauchessec, A. Lecomte, Alkaline dissolution potential of aluminosilicate minerals for the geosynthesis of mine paste backfill, Mater. Today Commun. 24 (2020), 101221.
[97] H.U. Ahmed, A.A. Mohammed, S. Rafiq, A.S. Mohammed, A. Mosavi, N.H. Sor, S.M.A. Qaidi, Compressive strength of sustainable geopolymer concrete composites: a state-of-the-art review, Sustainability 13 (24) (2021) 13502.
[98] M. Amin, A.M. Zeyad, B.A. Tayeh, I.S. Agwa, Effect of high temperatures on mechanical, radiation attenuation and microstructure properties of heavyweight geopolymer concrete, Struct. Eng. Mech. 80 (2) (2021) 181–199.
[99] M.M. Ahmed, K. El-Naggar, D. Tarek, A. Ragab, H. Sameh, A.M. Zeyad, B.A. Tayeh, I.M. Maafa, A. Yousef, Fabrication of thermal insulation geopolymer bricks using ferrosilicon slag and alumina waste, Case Stud. Constr. Mater. 15 (2021), e00737.
[100] A.L. Almutairi, B.A. Tayeh, A. Adesina, H.F. Isleem, A.M. Zeyad, Potential applications of geopolymer concrete in construction: a review, Case Stud. Constr. Mater. 15 (2021), e00733.
[101] N. Zhang, A. Hedayat, H.G. Bolaños Sosa, R.P. Huamani Bernal, N. Tupa, I. Yanqui Morales, R.S. Canahua Loza, Fracture properties of the gold mine tailings-based geopolymer under mode I loading condition through semi-circular bend tests with digital image correlation, Theor. Appl. Fract. Mech. 116 (2021), 103116.
[102] N. Zhang, A. Hedayat, H.G. Bolaños Sosa, J.J. González Cárdenas, G.E. Salas Álvarez, V.B. Ascuña Rivera, Damage evaluation and deformation behavior of mine tailing-based Geopolymer under uniaxial cyclic compression, Ceram. Int. 47 (8) (2021) 10773–10785.
[103] A.R.G. de Azevedo, M.T. Marvila, M. Ali, M.I. Khan, F. Masood, C.M.F. Vieira, Effect of the addition and processing of glass polishing waste on the durability of geopolymeric mortars, Case Stud. Constr. Mater. 15 (2021), e00662.
[104] M.T. Marvila, A.R.Gd Azevedo, C.M.F. Vieira, Reaction mechanisms of alkali-activated materials, Rev. IBRACON Estrut. Mater. 14 (2021).
[105] A.R.G. de Azevedo, M.T. Marvila, H.A. Rocha, L.R. Cruz, C.M.F. Vieira, Use of glass polishing waste in the development of ecological ceramic roof tiles by the geopolymerization process, Int. J. Appl. Ceram. Technol. 17 (6) (2020) 2649–2658.
[106] C. Anning, J. Wang, P. Chen, I. Batmunkh, X. Lyu, Determination and detoxification of cyanide in gold mine tailings: a review, Waste Manag. Res. 37 (11) (2019) 1117–1126.
[107] I. Park, C.B. Tabelin, S. Jeon, X. Li, K. Seno, M. Ito, N. Hiroyoshi, A review of recent strategies for acid mine drainage prevention and mine tailings recycling, Chemosphere 219 (2019) 588–606.
[108] G. Lazorenko, A. Kasprzhitskii, F. Shaikh, R.S. Krishna, J. Mishra, Utilization potential of mine tailings in geopolymers: physicochemical and environmental aspects, Process Saf. Environ. Prot. 147 (2021) 559–577.
[109] J.S. Adiansyah, M. Rosano, S. Vink, G. Keir, A framework for a sustainable approach to mine tailings management: disposal strategies, J. Clean. Prod. 108 (2015) 1050–1062.
[110] G. Mudd, D. Boger, The ever growing case for paste and thickened tailings—towards more sustainable mine waste management, J. Aust. Inst. Min. Met. 2 (2013) 56–59.
[111] M. Edraki, T. Baumgartl, E. Manlapig, D. Bradshaw, D.M. Franks, C.J. Moran, Designing mine tailings for better environmental, social and economic outcomes: a review of alternative approaches, J. Clean. Prod. 84 (2014) 411–420.
[112] J. Kiventerä, L. Golek, J. Yliniemi, V. Ferreira, J. Deja, M. Illikainen, Utilization of sulphidic tailings from gold mine as a raw material in geopolymerization, Int. J. Miner. Process. 149 (2016) 104–110.
[113] L. Weber, T. Leek, A. Alzubairi, An economic analysis of the extraction of rare earth elements from WPPA sand tailings waste stream, (2015).
[114] C. Qi, A. Fourie, Cemented paste backfill for mineral tailings management: review and future perspectives, Miner. Eng. 144 (2019), 106025.
[115] B.G. Lottermoser, Recycling, reuse and rehabilitation of mine wastes, Elements 7 (6) (2011) 405–410.
[116] Z. Xiaolong, Z. Shiyu, L. Hui, Z. Yingliang, Disposal of mine tailings via geopolymerization, J. Clean. Prod. 284 (2021), 124756.
[117] D. Kossoff, W. Dubbin, M. Alfredsson, S. Edwards, M. Macklin, K.A. Hudson-Edwards, Mine tailings dams: characteristics, failure, environmental impacts, and remediation, Appl. Geochem. 51 (2014) 229–245.
[118] J. Ye, W. Zhang, D. Shi, Properties of an aged geopolymer synthesized from calcined ore-dressing tailing of bauxite and slag, Cem. Concr. Res. 100 (2017) 23–31.
[119] J. Ye, W. Zhang, D. Shi, Effect of elevated temperature on the properties of geopolymer synthesized from calcined ore-dressing tailing of bauxite and ground-granulated blast furnace slag, Constr. Build. Mater. 69 (2014) 41–48.
[120] X. Li, P. Wang, Z. Guo, J. Qin, K. Liang, Effect of $Fe^{2+}/Fe^{3+}$ on high-strength ceramsite prepared by sintering geopolymers using iron ore tailings, Ceram. Int. (2021).
[121] P. Duan, C. Yan, W. Zhou, D. Ren, Fresh properties, compressive strength and microstructure of fly ash geopolymer paste blended with iron ore tailing under thermal cycle, Constr. Build. Mater. 118 (2016) 76–88.
[122] P. Duan, C. Yan, W. Zhou, D. Ren, Development of fly ash and iron ore tailing based porous geopolymer for removal of Cu(II) from wastewater, Ceram. Int. 42 (12) (2016) 13507–13518.
[123] K. do Carmo e Silva Defáveri, L.F. dos Santos, J.M. Franco de Carvalho, R.A.F. Peixoto, G.J. Brigolini, Iron ore tailing-based geopolymer containing glass wool residue: a study of mechanical and microstructural properties, Constr. Build. Mater. 220 (2019) 375–385.
[124] L.F. dos Santos, J.M.F. de Carvalho, R.A.F. Peixoto, G.J. Brigolini, Iron ore tailing-based geopolymer containing glass wool residue: a study of mechanical and microstructural properties, Constr. Build. Mater. 220 (2019) 375–385.
[125] B. Sternal, J. Junttila, K. Skirbekk, M. Forwick, J. Carroll, K.B. Pedersen, The impact of submarine copper mine tailing disposal from the 1970s on Repparfjorden, northern Norway, Mar. Pollut. Bull. 120 (1–2) (2017) 136–153.
[126] P. Duan, C. Yan, W. Zhou, D. Ren, Development of fly ash and iron ore tailing based porous geopolymer for removal of Cu (II) from wastewater, Ceram. Int. 42 (12) (2016) 13507–13518.
[127] G. Cao, W. Wang, G. Yin, Z. Wei, Experimental study of shear wave velocity in unsaturated tailings soil with variant grain size distribution, Constr. Build. Mater. 228 (2019), 116744.
[128] Y. Haddaji, H. Majdoubi, S. Mansouri, Y. Tamraoui, M. El bouchti, B. Manoun, M. Oumam, H. Hannache, Effect of synthetic fibers on the properties of geopolymers based on non-heat treated phosphate mine tailing, Mater. Chem. Phys. 260 (2021), 124147.
[129] V.F.F. Barbosa, K.J.D. MacKenzie, Thermal behaviour of inorganic geopolymers and composites derived from sodium polysialate, Mater. Res. Bull. 38 (2) (2003) 319–331.
[130] J. Schön. Physical Properties of Rocks: A Workbook, Elsevier, 2011.
[131] M.B. Lindsay, M.C. Moncur, J.G. Bain, J.L. Jambor, C.J. Ptacek, D.W. Blowes, Geochemical and mineralogical aspects of sulfide mine tailings, Appl. Geochem. 57 (2015) 157–177.
[132] F.A. Kuranchie, S.K. Shukla, D. Habibi, Utilisation of iron ore mine tailings for the production of geopolymer bricks, Int. J. Min. Reclam. Environ. 30 (2) (2016) 92–114.

[133] L. Yu, Z. Zhang, X. Huang, B. Jiao, D. Li, Enhancement experiment on cementitious activity of copper-mine tailings in a geopolymer system, Fibers 5 (4) (2017) 47.

[134] B. Wei, Y. Zhang, S. Bao, Preparation of geopolymers from vanadium tailings by mechanical activation, Constr. Build. Mater. 145 (2017) 236–242.

[135] H. Cheng, C. Chen, S. Wu, Z.A. Mirza, Z. Liu, Emergy evaluation of cropping, poultry rearing, and fish raising systems in the drawdown zone of Three Gorges Reservoir of China, J. Clean. Prod. 144 (2017) 559–571.

[136] N. Niroshan, L. Yin, N. Sivakugan, R.L. Veenstra, Relevance of SEM to long-term mechanical properties of cemented paste backfill, Geotech. Geol. Eng. 36 (4) (2018) 2171–2187.

[137] B. Sharath, K. Shivaprasad, M. Athikkal, B. Das, Some studies on sustainable utilization of Iron Ore Tailing (IOT) as fine aggregates in fly ash based geopolymer mortar. IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2018.

[138] A. Sahi, K. El Mahboub, T. Belem, A. Maqsoud, M. Mbonimpa, Dewatering of mine tailings slurries using Superabsorbent Polymers (SAPs) reclaimed from industrial reject of baby diapers: a preliminary study, Minerals 9 (12) (2019) 785.

[139] H. Paiva, J. Yliniemi, M. Illikainen, F. Rocha, V.M. Ferreira, Mine tailings geopolymers as a waste management solution for a more sustainable habitat, Sustainability 11 (4) (2019) 995.

[140] A.M.T. Simonsen, S. Solismaa, H.K. Hansen, P.E. Jensen, Evaluation of mine tailings' potential as supplementary cementitious materials based on chemical, mineralogical and physical characteristics, Waste Manag. 102 (2020) 710–721.

[141] Y. Wu, B. Lu, T. Bai, H. Wang, F. Du, Y. Zhang, L. Cai, C. Jiang, W. Wang, Geopolymer, green alkali activated cementitious material: synthesis, applications and challenges, Constr. Build. Mater. 224 (2019) 930–949.

[142] L. Manjarrez, A. Nikvar-Hassani, R. Shadnia, L. Zhang, Experimental study of geopolymer binder synthesized with copper mine tailings and low-calcium copper slag, J. Mater. Civ. Eng. 31 (8) (2019), 04019156.

[143] M. Gitari, S. Akinyemi, R. Thobakgale, P. Ngoejana, L. Ramugondo, M. Matidza, S. Mhlongo, F. Dacosta, N. Nemapate, Physicochemical and mineralogical characterization of Musina mine copper and New Union gold mine tailings: Implications for fabrication of beneficial geopolymeric construction materials, J. Afr. Earth Sci. 137 (2018) 218–228.

[144] T. Falayi, A comparison between fly ash-and basic oxygen furnace slag-modified gold mine tailings geopolymers, Int. J. Energy Environ. Eng. (2019) 1–11.

[145] J. Kiventerä, H. Sreenivasan, C. Cheeseman, P. Kinnunen, M. Illikainen, Immobilization of sulfates and heavy metals in gold mine tailings by sodium silicate and hydrated lime, J. Environ. Chem. Eng. 6 (5) (2018) 6530–6536.

[146] H. Niu, M. Abdulkareem, H. Sreenivasan, A.M. Kantola, J. Havukainen, M. Horttanainen, V.-V. Telkki, P. Kinnunen, M. Illikainen, Recycling mica and carbonate-rich mine tailings in alkali-activated composites: a synergy with metakaolin, Miner. Eng. 157 (2020), 106535.

[147] J. Park, B. Lee, W. Shin, S. Jo, H. Jun, Psychrophilic methanogenesis of food waste in a bio-electrochemical anaerobic digester with rotating impeller electrode, J. Clean. Prod. 188 (2018) 556–567.

[148] Y. Luo, S. Bao, Y. Zhang, Preparation of one-part geopolymeric precursors using vanadium tailing by thermal activation, J. Am. Ceram. Soc. 103 (2) (2020) 779–783.

[149] X. Jiao, Y. Zhang, T. Chen, Thermal stability of a silica-rich vanadium tailing based geopolymer, Constr. Build. Mater. 38 (2013) 43–47.

[150] P. Perumal, K. Piekkari, H. Sreenivasan, P. Kinnunen, M. Illikainen, One-part geopolymers from mining residues–effect of thermal treatment on three different tailings, Miner. Eng. 144 (2019), 106026.

[151] A. Wang, H. Liu, X. Hao, Y. Wang, X. Liu, Z. Li, Geopolymer synthesis using garnet tailings from molybdenum mines, Minerals 9 (1) (2019) 48.

[152] J. McDonald, S. Roache, S. Kawatra, Repurposing mine tailings: cold bonding of siliceous iron ore tailings, Miner. Metall. Process. 33 (1) (2016) 47–52.

[153] M. Song, L. Jiaping, J. Qian, L. Jianzhong, S. Liang, Experimental study on utilization of quartz mill tailings as a filler to prepare geopolymer, Miner. Process. Extr. Metall. Rev. 37 (5) (2016) 311–322.

[154] Q. Wan, F. Rao, S. Song, C.A. Leon-Patino, Y. Ma, W. Yin, Consolidation of mine tailings through geopolymerization at ambient temperature, J. Am. Ceram. Soc. 102 (5) (2019) 2451–2461.

[155] G. Kastiukas, X. Zhou, J. Castro-Gomes, Preparation conditions for the synthesis of alkali-activated binders using tungsten mining waste, J. Mater. Civ. Eng. 29 (10) (2017), 04017181.

[156] L. Manjarrez, L. Zhang, Utilization of copper mine tailings as road base construction material through geopolymerization, J. Mater. Civ. Eng. 30 (9) (2018), 04018201.

[157] X. Tian, W. Xu, S. Song, F. Rao, L. Xia, Effects of curing temperature on the compressive strength and microstructure of copper tailing-based geopolymers, Chemosphere 253 (2020), 126754.

[158] P. Duan, C. Yan, W. Zhou, W. Luo, Fresh properties, mechanical strength and microstructure of fly ash geopolymer paste reinforced with sawdust, Constr. Build. Mater. 111 (2016) 600–610.

[159] E. Barrie, V. Cappuyns, E. Vassilieva, R. Adriaens, S. Hollanders, D. Garcés, C. Paredes, Y. Pontikes, J. Elsen, L. Machiels, Potential of inorganic polymers (geopolymers) made of halloysite and volcanic glass for the immobilisation of tailings from gold extraction in Ecuador, Appl. Clay Sci. 109 (2015) 95–106.

[160] P.H. Ribeiro Borges, F.C. Resende Ramos, T. Rodrigues Caetano, T. Hallak Panzerra, H. Santos, Reuse of iron ore tailings in the production of geopolymer mortars, REM Rev. Esc. Minas 72 (4) (2019).

[161] X. Zhu, W. Li, Z. Du, S. Zhou, Y. Zhang, F. Li, Recycling and utilization assessment of steel slag in metakaolin based geopolymer from steel slag by-product to green geopolymer, Constr. Build. Mater. 305 (2021), 124654.

[162] O. Mahmoodi, H. Siad, M. Lachemi, M. Sahmaran, Synthesis and optimization of binary systems of brick and concrete wastes geopolymers at ambient environment, Constr. Build. Mater. 276 (2021), 122217.

[163] O. Mahmoodi, H. Siad, M. Lachemi, S. Dadsetan, M. Sahmaran, Development of optimized binary ceramic tile and concrete wastes geopolymer binders for in-situ applications, J. Build. Eng. 43 (2021), 102906.

[164] O. Mahmoodi, H. Siad, M. Lachemi, S. Dadsetan, M. Sahmaran, Development of normal and very high strength geopolymer binders based on concrete waste at ambient environment, J. Clean. Prod. 279 (2021), 123436.

[165] G. Liang, H. Zhu, H. Li, T. Liu, H. Guo, Comparative study on the effects of rice husk ash and silica fume on the freezing resistance of metakaolin-based geopolymer, Constr. Build. Mater. 293 (2021), 123486.

[166] S. Gomes, L. Frezet, E. Petit, S. Petlickaia, S. Rossignol, N. Texier-Mandoki, G. Renaudin, Temperature stability of an argillite/K-geopolymer composite: impact of argillite filler on dimensional behavior, Open Ceram. 5 (2021), 100081.

[167] X. Ren, L. Zhang, D. Ramey, B. Waterman, S. Ormsby, Utilization of aluminum sludge (AS) to enhance mine tailings-based geopolymer, J. Mater. Sci. 50 (3) (2015) 1370–1381.

[168] L. Tchadjie, S. Ekolu, Enhancing the reactivity of aluminosilicate materials toward geopolymer synthesis, J. Mater. Sci. 53 (7) (2018) 4709–4733.

[169] L.N. Tchadjié, S.O. Ekolu, H. Quainoo, P. Tematio, Incorporation of activated bauxite to enhance engineering properties and microstructure of volcanic ash geopolymer mortar composites, J. Build. Eng. 41 (2021), 102384.

[170] G. Mucsi, S. Kumar, B. Csőke, R. Kumar, Z. Molnár, Á. Rácz, F. Mádai, Á. Debreczeni, Control of geopolymer properties by grinding of land filled fly ash, Int. J. Miner. Process. 143 (2015) 50–58.

[171] N. Marjanović, M. Komljenović, Z. Baščarević, V. Nikolić, Improving reactivity of fly ash and properties of ensuing geopolymers through mechanical activation, Constr. Build. Mater. 57 (2014) 151–162.

[172] S. Kushwah, M. Mudgal, R.K. Chouhan, The process, characterization and mechanical properties of fly ash-based solid form geopolymer via mechanical activation, South Afr. J. Chem. Eng. 38 (2021) 104–114.

[173] S. Kumar, G. Mucsi, F. Kristály, P. Pekker, Mechanical activation of fly ash and its influence on micro and nano-structural behaviour of resulting geopolymers, Adv. Powder Technol. 28 (3) (2017) 805–813.

[174] S. Kumar, R. Kumar, Mechanical activation of fly ash: effect on reaction, structure and properties of resulting geopolymer, Ceram. Int. 37 (2) (2011) 533–541.

[175] A.D. Hounsi, G.L. Lecomte-Nana, G. Djétéli, P. Blanchart, Kaolin-based geopolymers: effect of mechanical activation and curing process, Constr. Build. Mater. 42 (2013) 105–113.
[176] A.Z. Khalifa, Ö. Cizer, Y. Pontikes, A. Heath, P. Patureau, S.A. Bernal, A.T. Marsh, Advances in alkali-activation of clay minerals, Cem. Concr. Res. 132 (2020), 106050.
[177] M. Falah, R. Obenaus-Emler, P. Kinnunen, M. Illikainen, Effects of activator properties and curing conditions on alkali-activation of low-alumina mine tailings, Waste Biomass Valoriz. (2019) 1–13.
[178] S. Ahmari, L. Zhang, Durability and leaching behavior of mine tailings-based geopolymer bricks, Constr. Build. Mater. 44 (2013) 743–750.
[179] S. Ahmari, X. Ren, V. Toufigh, L. Zhang, Production of geopolymeric binder from blended waste concrete powder and fly ash, Constr. Build. Mater. 35 (2012) 718–729.
[180] S. Ahmari, L. Zhang, J. Zhang, Effects of activator type/concentration and curing temperature on alkali-activated binder based on copper mine tailings, J. Mater. Sci. 47 (16) (2012) 5933–5945.
[181] T. Falayi, Effect of potassium silicate and aluminate on the stabilisation of gold mine tailings. Proceedings of the Institution of Civil Engineers-Waste and Resource Management, Thomas Telford Ltd., 2019, pp. 56–63.
[182] W. Pardavé, M. Epalza, J. Durán, D.F. Lóvera, Obtaining a cementitious geopolymer from gold mining tailings with possible use in engineering applications, Am. J. Eng. Res. (AJER) 7 (2018) 137–142.
[183] J. Kiventerä, J. Yliniemi, L. Golek, J. Deja, V. Ferreira, M. Illikainen, Utilization of sulphidic mine tailings in alkali-activated materials, MATEC Web of Conferences, EDP Sci. (2019) 01001.
[184] S. Solismaa, A. Ismailov, M. Karhu, H. Sreenivasan, M. Lehtonen, P. Kinnunen, M. Illikainen, M.L. Räisänen, Valorization of Finnish mining tailings for use in the ceramics industry, Bull. Geol. Soc. Finl. 90 (1) (2018).
[185] Q. Wan, F. Rao, S. Song, Y. Zhang, Immobilization forms of ZnO in the solidification/stabilization (S/S) of a zinc mine tailing through geopolymerization, J. Mater. Res. Technol. 8 (6) (2019) 5728–5735.
[186] J. Ye, W. Zhang, D. Shi, Performance evolutions of tailing-slag-based geopolymer under severe conditions, J. Sustain. Cem. Based Mater. 4 (2) (2015) 101–115.
[187] Y. Haddaji, H. Majdoubi, S. Mansouri, Y. Tamraoui, B. Manoun, M. Oumam, H. Hannache, Effect of synthetic fibers on the properties of geopolymers based on non-heat treated phosphate mine tailing, Mater. Chem. Phys. 260 (2021), 124147.
[188] S. Ahmari, L. Zhang, Production of eco-friendly bricks from copper mine tailings through geopolymerization, Constr. Build. Mater. 29 (2012) 323–331.
[189] S. Ahmari, K. Parameswaran, L. Zhang, Alkali activation of copper mine tailings and low-calcium flash-furnace copper smelter slag, J. Mater. Civ. Eng. 27 (6) (2015), 04014193.
[190] L. Zhang, S. Ahmari, J. Zhang, Synthesis and characterization of fly ash modified mine tailings-based geopolymers, Constr. Build. Mater. 25 (9) (2011) 3773–3781.
[191] J. Kiventerä, I. Lancellotti, M. Catauro, F. Dal Poggetto, C. Leonelli, M. Illikainen, Alkali activation as new option for gold mine tailings inertization, J. Clean. Prod. 187 (2018) 76–84.
[192] Q. Yuan, C. Shi, G. De Schutter, K. Audenaert, D. Deng, Chloride binding of cement-based materials subjected to external chloride environment–a review, Constr. Build. Mater. 23 (1) (2009) 1–13.
[193] F. El Meski, G. Chehab, Flexural behavior of concrete beams reinforced with different types of geogrids, J. Mater. Civ. Eng. 26 (8) (2014), 04014038.
[194] X. Jiao, Y. Zhang, T. Chen, S. Bao, T. Liu, J. Huang, Geopolymerisation of a silica-rich tailing, Miner. Eng. 24 (15) (2011) 1710–1712.
[195] E. Caballero, W. Sánchez, C.A. Ríos, Synthesis of geopolymers from alkaline activation of gold mining wastes, Ing. Y. Compet. 16 (1) (2014) 317–330.
[196] G. Liang, H. Zhu, Z. Zhang, Q. Wu, Effect of rice husk ash addition on the compressive strength and thermal stability of metakaolin based geopolymer, Constr. Build. Mater. 222 (2019) 872–881.
[197] H.Y. Zhang, G.H. Qiu, V. Kodur, Z.S. Yuan, Spalling behavior of metakaolin-fly ash based geopolymer concrete under elevated temperature exposure, Cem. Concr. Compos. 106 (2020), 103483.
[198] R. Kumar, P. Das, M. Beulah, H. Arjun, G. Ignatius, Utilization of iron ore tailings for the production of fly ash—GGBS-based geopolymer bricks, J. Adv. Manuf. Syst. 16 (03) (2017) 275–290.