

Review

Review of Recent Developments Regarding the Durability Performance of Eco-Friendly Geopolymer Concrete

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Abstract: The 21st century has witnessed a substantial increase in the demand for construction materials, mainly influenced by the growing population. This increase in demand has resulted in higher prices for these materials and has also placed considerable burdens on environmental resources, prompting the search for eco-friendly and economically viable alternatives such as geopolymer materials to replace traditional materials like cement. The benefits of geopolymer materials as substitutes for cement in concrete extend beyond their exceptional durability. Initially, geopolymer was introduced to address the environmental impact arising from carbon dioxide emissions and the substantial consumption of fossil fuels through the production of cement. The current review investigates recent advances regarding the durability characteristics of geopolymer materials. This includes aspects such as water absorption, temperature resistance, sulfuric acid resistance, sulfate resistance, chloride ion penetration, and freeze–thaw resistance, among others. The results of this review highlight geopolymer concrete’s enhanced durability over traditional cement-based concrete. Furthermore, this review offers recommendations and outlines potential research avenues for further exploration of geopolymer concrete.

Keywords: abrasion; corrosion; durability properties; fire resistance; freeze–thaw resistance; geopolymer concrete; sodium chloride; sulfate resistance; sulfuric acid; water absorption



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1. Introduction

Climate change stands as one of humanity’s most pressing and serious challenges. The greenhouse gases released, with carbon dioxide (CO₂) being of particular concern, primarily fuel the acceleration of climate change [1] and air pollution [2]. The climate and its resources must be protected while environmentally friendly development is promoted [3]. In this modern world, environmental and economic concerns continue to rise regarding traditional concrete-based construction materials. In order to address these challenges, many researchers have been actively involved in the investigation of substitute materials [4]. The global manufacturing of cement is accountable for significant CO₂ emissions, contributing approximately 7–9% of the total CO₂ emissions worldwide [5,6]. Cement, when mixed with water and aggregates, gives rise to cement-based materials such as concrete and stands as the most massively manufactured product on Earth [7–9]. Concrete ranks as the second most widely used material worldwide, trailing only behind potable water in terms of utilization. Its origins can be traced back to the Ancient Egyptian and Roman civilizations [10–12]. It is made and transported with significant CO₂ emissions [13]. The annual production of concrete is approximately 4.4 billion metric tons worldwide, and this figure is projected to rise to 5.5 billion metric tons by 2050 [14,15]. The main ingredient utilized in the creation of concrete is ordinary Portland cement (OPC) [16–19]. The

growing demand for concrete demonstrates a predictable upward growth in cement manufacturing, and it is expected to rise from 4.3 to 6.1 billion metric tons from 2015 to 2050, respectively [20]. However, there is a depletion of natural resources due to OPC production, where 1 ton of OPC production needs 1.7 tons of raw materials [20–23]. The annual CO₂ emissions from OPC production are estimated to be around 4 billion tons [18,24]. In the context of energy consumption and the decarbonization process applied in the conversion of limestone, about 1 ton of CO₂ is released per ton of cement production [25–30]. The International Energy Agency (IEA) reported that these emissions account for 5–8% of total CO₂ emissions globally [31–38]. In addition, OPC emits nitrogen oxides and sulfur oxides [39]. As a result, every nation is now obligated to contemplate regulations for and reductions in CO₂ emissions [40]. On the other hand, in the context of the rising population, economic growth, fast urbanization, and infrastructure development [41], waste production has significantly increased globally in the last few decades. Statistical studies predicted that by 2050, global waste production will have doubled the figure from 2016 to 3.40 billion tons and tripled by 2100 [42]. As of late, a growing focus on sustainable construction materials, particularly geopolymers (GPC), has drawn considerable attention [43]. Looking at its history, in the 1970s, Prof. Joseph Davidovits and French researchers invented the term “geopolymer” [44–51]. Recently, GPC has gained recognition as the successor to conventional lime and Portland cement concrete [3]. GPC formation requires the activation of a pozzolanic material abundant in silicon (Si) and aluminum (Al) using an alkaline solution [14,52]. This process is termed “geopolymerization” and it is a multistep process that includes leakage, dispersion, reorientation, polymerization, and condensation [53]. Polymerization takes place through a condensation process where heat is liberated during the endothermic reaction of geopolymers [54]. An alkaline activator solution, commonly composed of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate (Na₂SiO₃) or potassium silicate (K₂SiO₃), is crucial for the production of Si and Al crystalline structures [55]. However, a mixture of NaOH and Na₂SiO₃ is the most popular alkaline solution due to the lower cost and better availability of sodium-based compounds compared to potassium-based compounds [56]. The optimal curing of fresh GPC is the linchpin of the entire geopolymerization process, as it plays a vital role in maximizing compressive strength. Generally, GPC is cured using various methods, such as oven curing, steam curing, ambient temperature curing, and so on [48,57,58]. GPC exhibits excellent initial compressive strength, minimal shrinkage, and notable resistance to creep, and it is well-suited for acidic environments [59,60].

Fly ash (FA) and glass-granulated blast-furnace slag (GGBS) have gained traction in landfill sites, since they are widely available and possess high silica and alumina contents, replacing metakaolin as the primary binding component in concrete [1,61,62]. FA is a byproduct produced in thermal power plants, while GGBS is a waste material originating from blast furnaces. Both FA and GGBS undergo suitable treatment processes before being utilized as geopolymer materials in construction projects [47]. In addition, other waste materials were used to produce GPC, such as rice husk ash [63], waste glass [64], palm oil fuel ash [65], ceramic waste [66], bagasse ash [39], illitic clay [67], Moroccan clays [68], clay minerals [69], and smectite clay [70], silica fume [65], waste clay brick [71], waste bricks powder [72], sewage sludge ash [73], and basalt powder [74]. Alkali-activated materials can generally be divided into two groups: (a) the high calcium system, where GGBS is a representative precursor and results in the formation of a C–A–S–H type gel as the main reaction product; and (b) the low calcium system, where class F FA and metakaolin are representative raw materials and produce N–A–S–H type gels within a three-dimensional network as the main reaction product [75]. Under alkaline conditions, a rapid interaction between silica and alumina is necessary to speed up the polymerization process. This occurrence leads to the formation of a 3D (three-dimensional) polymeric bond chain called the Si–O–Al–O bond [76,77]. The polymerization process, as depicted in Figure 1, can be used to describe the chemical reaction between aluminosilicate oxide and alkali polysilicate [78].

The chemical compositions of different materials used to produce GPC from various sources were subjected to analysis through X-ray fluorescence (XRF), and the consolidated data are presented in Table 1. In addition, natural resources like river sand and coarse aggregate are needed in enormous quantities to produce such a massive volume of concrete. According to the estimate, the world's construction needs would require 35 billion tons of cobblestone aggregates and sand [79]. Since aggregates make up more than 70–80% of the concrete matrix, they are one of the main components of concrete. Natural aggregates that are suitable for construction are scarce in many countries, although their consumption is rising in other nations as a result of increased demand from the construction sector [80–82]. Both coarse aggregates (with particle sizes of more than 4.75 mm) and fine aggregates (with particle sizes of less than 4.75 mm) are used as forms of aggregates [83]. As a result, industrial waste such as copper slag can be used as an alternative. Figure 2 illustrates the components found in geopolymer concrete.

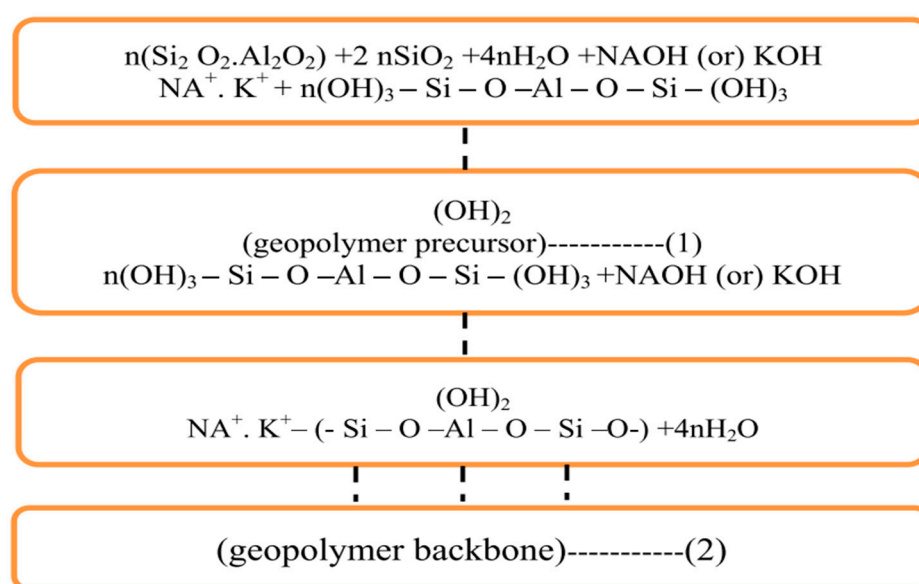


Figure 1. Polymerization reaction [78,84].

Table 1. The chemical compositions of different materials used to produce GPC.

References	Constituents (%)	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	SO ₃	LOI
[85]	Fly ash	63.32	26.76	2.49	5.55	0.29	0.0004	0.0002	0.36	0.97
[33]		56.00	24.00	4.00	7.00	2.00	-	-	-	3.00
[86]		54.62	24.27	6.14	8.389	1.134	0.258	0.801	0.279	2.704
[87]		61.74	25.23	2.15	5.98	0.32	-	-	0.27	2.15
[88]		58.60	23.60	3.13	7.45	0.90	0.18	1.65	0.80	2.015
[89]		53.04	34.70	2.32	2.53	0.86	0.48	1.75	0.84	2.52
[90]		52.86	34.19	2.57	3.85	2.01	-	-	-	1.30
[91]		60.11	26.53	4.00	4.25	1.25	0.22	-	0.35	-
[85]		35.05	12.50	34.64	0.30	6.34	0.9	0.6	0.38	0.26
[43]		34.80	15.78	36.81	0.38	7.09	0.27	0.44	2.53	1.5
[73]	GGBS	37.73	14.42	37.34	1.11	8.71	-	-	0.39	1.41
[87]		31.36	13.16	39.21	2.34	6.56	-	-	1.4	1.68
[89]		34.60	15.99	37.72	0.46	6.18	0.43	0.34	0.10	0.39
[90]		36.70	12.61	47.32	0.22	2.05	-	-	-	0.93
[92]		32.47	9.94	32.45	1.25	9.31	0.31	0.85	0.82	3.6
[91]		34.06	20.00	32.6	0.80	7.89	-	-	0.90	-
[93]		71.74	20.67	0.04	1.73	0.83	0.36	3.12	-	0.63
[74]		56.65	34.45	0.12	2.16	0.01	-	0.47	-	1.89

Table 1. Cont.

References	Constituents (%)	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	SO ₃	LOI
[94]	Silica fume	47.70	50.53	0.03	0.23	0.02	0.26	0.11	-	8.34
[20]		83.40	1.2	0.40	0.60	8.80	1.00	1.40	0.6	5.80
[15]		97.99	0.00	0.664	0.099	0.001	-	0.123	0.394	-
[65]		92.26	0.86	0.00	1.97	0.96	0.42	1.31	0.33	-
[71]	WCB	69.0	8.7	3.4	12.1	0.1	-	4.5	0.3	-
[72]	WBP	58.8	19.6	6.9	5.7	2.8	1.5	2.9	0.7	-
[73]	SCBA	73.40	3.66	3.02	3.26	2.56	0.68	4.26	1.05	5.16
[34]	SSA	41.4	1.24	26.1	1.24	2.95	-	11.1	7.36	0.47
[73]		35.40	9.56	24.70	5.56	4.06	0.72	2.57	5.19	3.50
[63]	RHA	96.03	0.01	0.53	0.13	-	-	1.67	0.19	1.45
[64]	WG	83.34	-	7.28	-	-	9.38	-	-	-
[74]	BP	44.5	15.4	9.83	13.98	6.20	2.76	1.51	-	1.04

Legend: WCB = waste clay brick, WBP = waste brick powder, SCBA = sugarcane bagasse ash, SSA = sewage sludge ash, RHA = rice husk ash, WG = waste glass, BP = basalt powder.

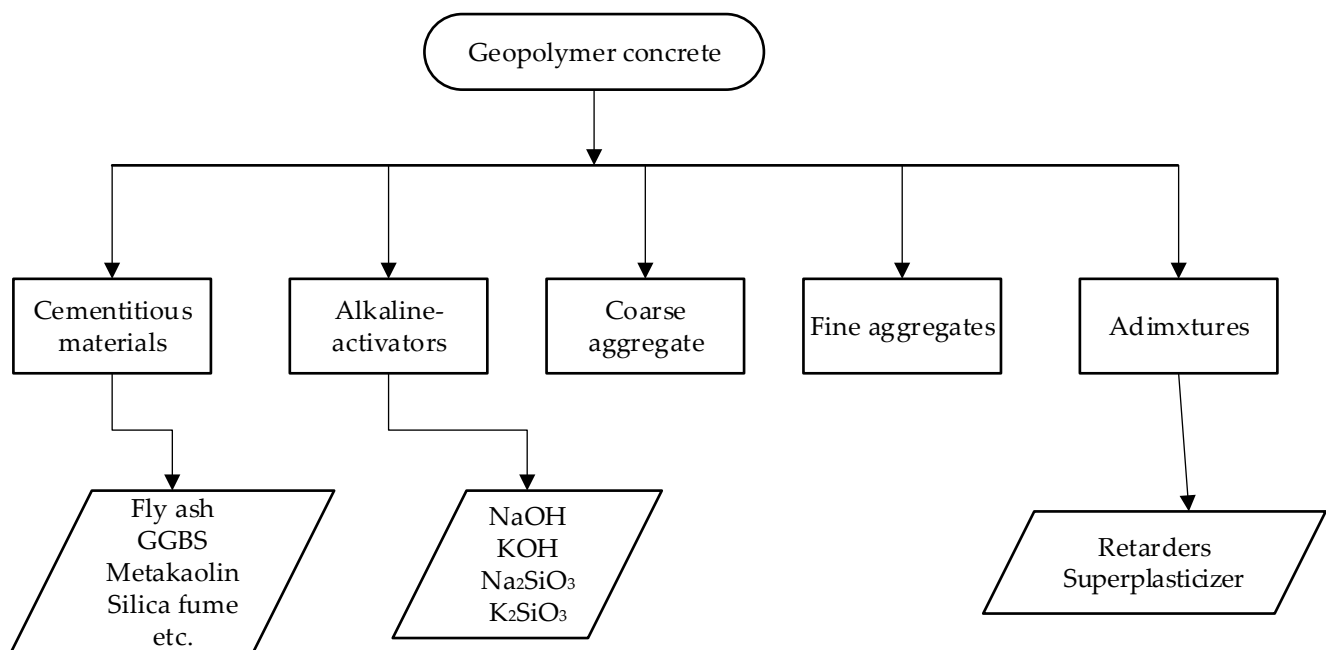


Figure 2. Geopolymer concrete constituents [95].

Contrary to traditional cement-based concrete, the use of GPC is estimated to potentially reduce energy consumption by 44–64% and reduce carbon emissions by 9–80%. This observation range of emissions reduction is attributed to the intricate nature of emissions calculations, which vary based on numerous factors, such as local conditions, the specific design and transportation mix, and so on [73,96–98]. As an illustration, the geopolymer binder generates CO₂ emissions ranging from 0.184 to 0.218 tons due to the combustion of carbon fuel, in contrast to 1 ton of CO₂ emitted by OPC [99]. The advantages of GPC materials are the sustainability of the building, a longer useful life, reduced use of virgin materials, recycling of industrial waste, significant life-cycle cost savings, and low carbon emissions [100]. In general, GPC marked an essential innovation in the field of concrete technology, specifically aimed at mitigating carbon dioxide emissions but also at eliminating material from landfills, thus allowing sustainable construction [101–103]. Thus, green cement-free GPC can be deemed a feasible substitute for traditional OPC concrete or concrete [32,104]. Figure 3 illustrates the efficacy of GPC in construction.

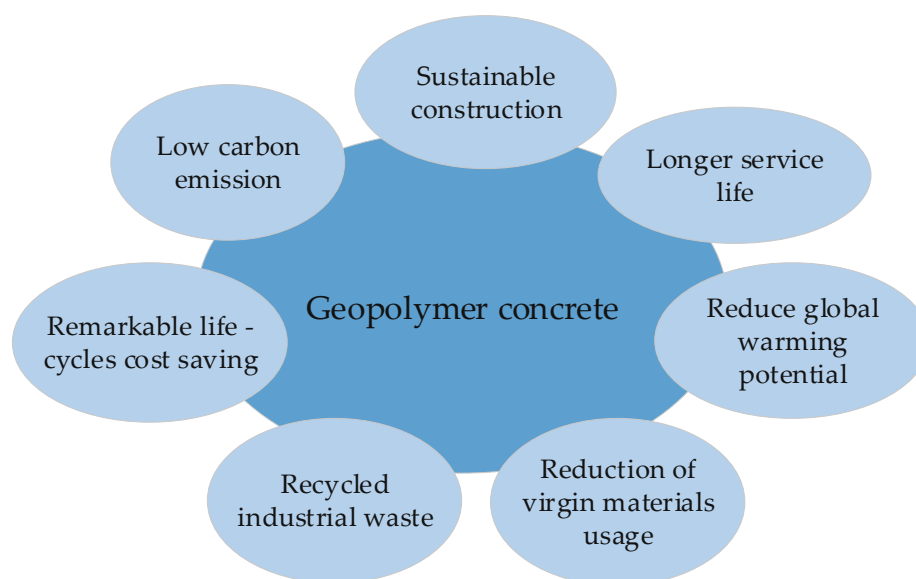


Figure 3. The efficacy of GPC in construction [100].

Pasupathy [42] reported that GPC has the potential to reduce embodied energy and carbon emissions by nearly 60–80% compared with OPC concrete. Also, Munir [14] concluded that the environmental impact of industrial waste processing and curing for concrete formulations is less than 1%. In addition, Mashri et al. [65] utilized a significant amount of palm oil fuel ash, eggshell ash, and silica fume in geopolymer mortar manufacturing, and they concluded that geopolymer could offer a viable solution to address environmental concerns and landfill disposal issues by promoting a greener alternative to Portland cement binder, with the potential for enhanced properties and performance. Likewise, Sherwani et al. [33] reported that slag and fly ash were used as binders and concluded that their findings could lead to more environmentally friendly concrete using geopolymers rather than OPC. Furthermore, Manikandan [105] stated that the use of geopolymer mortar for structural repair has shown great promise and proposed that additional investigations be carried out on the use of this mortar for structural repair. In the study by van Roosmale et al. [106], the activation of metakaolin-based GPC within the context of stone preservation was examined. They noted that the specimens exhibited a substantial open porosity, resulting in a lower density compared to findings in the existing literature about geopolymers with aggregates. However, the outcomes were in line with those of non-aggregate geopolymers. Occhipinti et al. [107] reported that combining Aeolian pumice with small proportions (20–30 wt.%) of metakaolin is viable for creating lightweight geopolymers. These geopolymers display an open porosity of up to 30%, approximately 18.0% water absorption, and a favorable 28-day compressive strength reaching up to 12 MPa. These figures provide evidence of excellent breathability and compatibility with the substrates in the suggested formulations. In the research by Ricciotti et al. [108], the establishment of a seamless connection between the geopolymer composite and both tuff and concrete surfaces was noted, emphasizing the strong compatibility of the geopolymer binder with diverse materials. These attributes signal significant potential for the use of these materials in cultural heritage preservation.

In conclusion, waste materials are now facing hindrances to cement manufacturing due to a lack of thorough knowledge regarding their impact on geopolymer materials. Therefore, researchers may need to conduct further studies on various geopolymer materials.

2. Materials and Methods Adopted for the Review

Information was gathered from the Elsevier, Springer, MDPI, Taylor & Francis, Wiley, Scopus, and ScienceDirect databases before a full discussion and evaluation of GPC's durability performance, which includes the resistances to water absorption, high temperatures,

sulfuric acid, sulfate corrosion, chloride ion penetration, abrasion, and freeze–thaw. The needed data were obtained through analysis and evaluation of the data through tables, graphs, and discussions leading to the formulation of conclusions. The methodology selected for the review is illustrated in Figure 4.

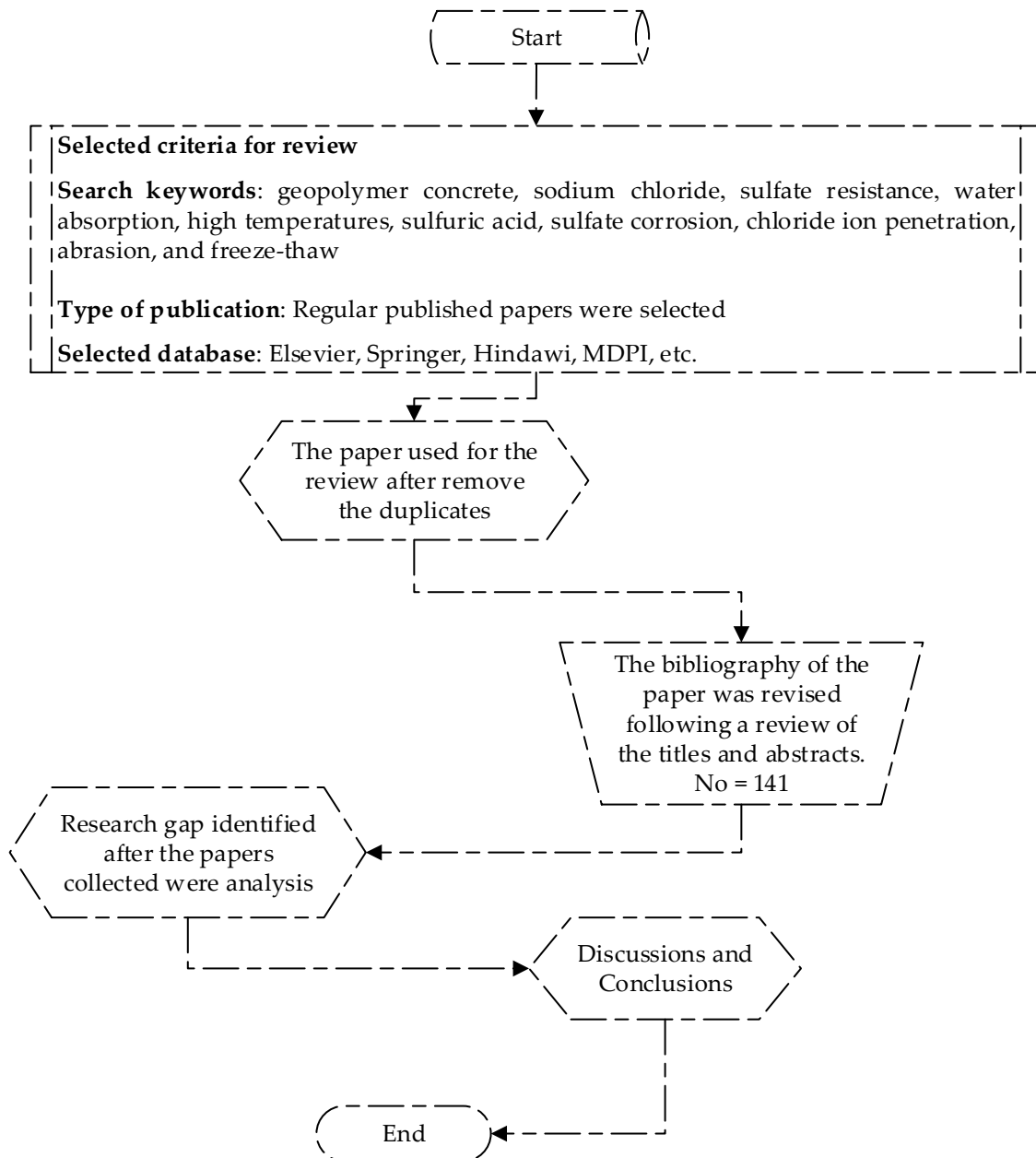


Figure 4. The methodology selected for the review.

3. Durability Performance of Geopolymer Concrete

Concrete materials are considered to have the capacity to endure and withstand adverse conditions or surroundings [109]. Long-term durability has always been a significant concern for OPC concrete in harsh surroundings. The assessment of concrete degradation generally involves the examination of its resistances to acidic chemicals, sulfate attack, elevated temperatures, chloride-induced corrosion, atmospheric influences, carbonation, alkali–silica reaction, freeze–thaw attack, and related factors [109,110]. In addition, the structural performance of concrete in harsh environments, particularly in coastal regions, necessitates a crucial emphasis on durability [111].

3.1. Water Absorption

The water absorption of the concrete structure significantly affects the durability of the structure [111]. Water penetration leads to the degradation of both concrete and reinforcement within the structure. For instance, the research by Saloni et al. [112] assessed the water absorption of GPC using fine rice husk ash (FRHA) replacing OPC at various contents of 0, 5, 10, 15, 20, 25, and 30%. They found a progressive decrease in water absorption with the increase in the FRHA proportion to 15% for all the curing ages, suggesting improved durability performance. In the study by Nagajothi et al. [85], the water absorptions of GPC at 28, 56, and 90 days were evaluated via the use of aluminosilicate materials (fly ash and GGBS) with alkaline activator solutions. The findings indicated that the reduction in the water absorption percentage in GPC was less compared to traditional concrete. This reduction is attributed to the pores occupied by fine slag particles, while the increase in water absorption in fly ash-based alkali-activated mixtures with slag-based binders led to a decrease in water absorption [113]. Moreover, the research by Mansourghanaei et al. [114] determined the effect of silica nanoparticles on slag-based GPC containing 0–2% polyolefin fibers and 0–8% nano-silica. In accordance with the results, the addition of nano-silica led to a notable reduction in both the permeability coefficients and water absorption, with decreases of up to 44, and 24, respectively. This drop was linked to the concrete's nano-densification silicas and pore-filling properties. Also, in another study by Ojha and Aggarwal [115], the long-term performance of low-calcium fly ash-based GPC with ordinary Portland cement concrete was compared in terms of the water absorption, water permeability, and sorptivity. The results demonstrated that, as compared with regular Portland cement concrete, geopolymer concrete displayed lower sorptivity, shallower water penetration, and reduced water absorption. These are the benefits of the presence of bigger voids in traditional concrete, although the enhanced properties of geopolymer concrete can be linked to the development of a denser microstructure. Likewise, Adam et al. [116] examined the effect of an alteration in the activator-to-binder ratio, ranging from 0.45 to 0.60 in increments of 0.05, on the water absorption of geopolymer concrete cured under ambient conditions. They observed that geopolymer concrete achieved its lowest levels of water absorption and permeable voids when the activator-to-binder ratio was at its highest value. Gupta et al. [87] studied the water absorption characteristics of geopolymer concrete composites by altering the concentrations of superplasticizers. Two sets of samples were created, each with varying superplasticizer levels (1%, 2%, and 3%). The first set exclusively contained GGBS, whereas the second set consisted of a 50% mixture of GGBS and fly ash. They concluded that the water absorption decreased as the superplasticizer dosage increased, and as a result, a 3% superplasticizer dosage resulted in minimal water absorption, as shown in Figure 5. Abbass and Singh [117] investigated the water absorption of geopolymer concrete-based sugarcane bagasse ash (SCA) and RHA coupled with high-strength basalt (BS) fibers at ratios of 0.5, 1.0, 1.5, 2.0, and 2.5%. The research results highlighted that exceeding 1% in fiber content resulted in heightened water absorption. This is attributed to the increase in air entrapment and decrease in bonding between the fibers and the GPC paste with the increasing fiber volumes.

This review observed that the absorption rate of geopolymer concrete is much lower than that of conventional Portland cement concrete. This is due to the amorphous form of the particles filling the pores created by the geopolymerization process, which reduces the porousness and density of the microstructure.

3.2. Fire Resistance

The residual compressive strength, also known as the post-damage compressive strength, denotes the maximum load a damaged material can support during loading. The capacity of geopolymer concrete to inhibit crack propagation has a significant impact on its residual compressive strength. In general, exposure to heat is one of the most significant factors that affect the properties, surface appearance, shape, and color of concrete [114]. For instance, in the research by Gupta et al. [87], the effect of elevated temperatures was

examined between 100–700 °C at 100 °C intervals on high-strength geopolymer concrete (HSGC) composed of FA, metakaolin, and granulated blast furnace slag. The results suggest that the strength reduction observed in the GPC mixes subjected to temperatures from 200 to 700 °C is primarily due to thermal incompatibility between the geopolymer matrix and aggregates. This incompatibility leads to the separation of the matrix from the aggregates, resulting in internal cracks. One significant factor contributing to concrete spalling is the buildup of pore pressure, and reducing the amount of evaporation water can mitigate this issue. Luhar et al. [118] examined the compressive strength of fly-ash-based GPC (as reference GPC) and rubberized GPC specimens. Figure 6 shows the trend in the GPC specimens' compressive strength growth. It can be seen that for all the temperatures, the decrease in the rubberized GPC's compressive strength was marginally less than that of the reference GPC. At temperatures of 200 and 800 °C, respectively, the compressive strength of the rubberized GPC exhibited reductions of 31.23% and 52.43%. However, at 200 and 800 °C, the decrease percentage values in the reference GPC's strength were found to be 27.38 and 45.22%, respectively. This was due to the rubber tire fibers' soft and lightweight characteristics, which were known to cause cracks in GPC specimens during the early compression stage. The rubberized GPC's larger strength decreases at high temperatures compared to the reference GPC are attributed to the tendency of rubber tire fibers to capture air and form void.

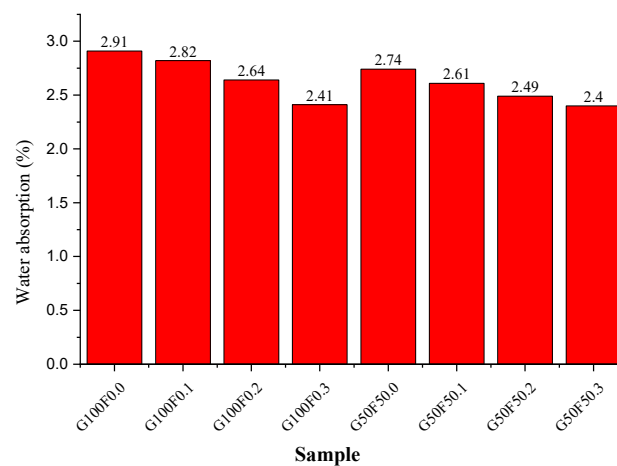


Figure 5. Water absorptions at 28 days for different dosages of superplasticizer [87].

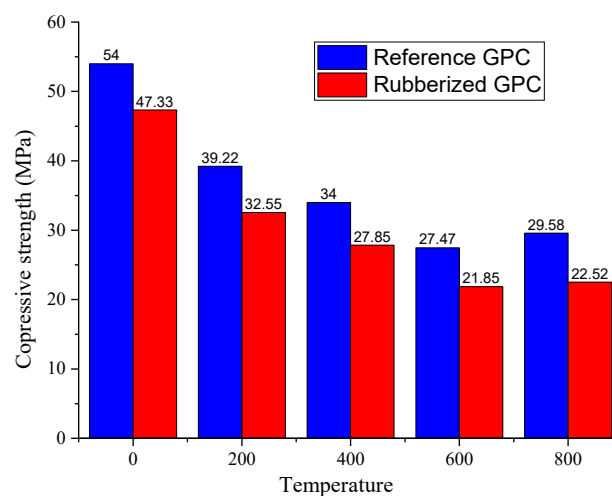


Figure 6. Compressive strengths of the test specimens made of reference and rubberized geopolymer concrete after being exposed to high temperatures [118].

It is observed that, unlike OPC hydration products, geopolymer concrete is chemically stable and does not experience chemical structural breakdown when subjected to high temperatures.

3.3. Sulfuric Acid Resistance

In terms of GPC, scientists are looking into how the breakdown of the aluminosilicate network structure is caused by the release of silicic acid ($\text{Si}(\text{OH})_4$) in acidic environments [119]. While it has been discovered that cementation particles and calcium-rich aggregates inside OPC concrete can dissolve and cause acid-induced degradation, when subjected to an acidic surrounding, OPC concrete is equally deteriorated. This could be the result of the development of water-soluble calcium compounds as a result of the acid-leaching effect on the OPC concrete. In order to ensure durability, assessment of the acid resistances of GPC and OPC concrete is essential [32]. For example, Ariffin et al. [120] explored a GPC mixture that included alkaline activators, a solution containing a certain percentage of sulfuric acid, and a combination of pulverized fuel ash (PFA) and palm oil fuel ash (POFA). This mixture was subjected to a sulfuric acid solution for a period exceeding one year. They concluded that the geopolymer concrete performed better than OPC concrete, as illustrated in Figure 7. The main reason for this is that the GPC creates a more durable cross-linked aluminosilicate polymer structure. Moreover, Lavanya and Jegan [111] examined the resistance of high calcium fly ash- and alkaline activator-made geopolymer concrete for up to 45 days in a solution of 2% sulfuric acid. The grades M20, M40, and M60 were used for the study. The findings revealed that the specimens' edges and surfaces appeared to be slightly harmed. Figure 8 demonstrates this. Furthermore, small and isolated cracks were detected. Similarly, with prolonged exposure, the density of the geopolymer concrete specimens steadily declined. The interaction between the acid and the specimens treated with calcium hydroxide can generate tensile stresses, potentially leading to the cracking and scaling of the concrete. As can be seen, the OPC density decreased by 5–7%, while the GPC density decreased by 2.5–4%. The fly ash's siliceous components also interacted to create a more stable C–S–H product, which further filled the pores in mortars. Also influencing the density drop was the fly ash's fineness [121]. In the research by Bakharev [122], the long-term performance of geopolymer materials incorporating alkaline activators and class F FA when subjected to 5% acetic and sulfuric acid solutions was assessed. The research revealed that the geopolymer materials produced with sodium hydroxide and subjected to high-temperature curing exhibited the most favorable performance. The improved performance of this material was credited to the development of a stronger cross-linked aluminosilicate polymer structure within it.

Albitar et al. [123] assessed the efficacy of GPC produced from either class F fly ash or a combination of fly ash and granulated lead smelter slag (GLSS) concerning their response to sulfuric acid exposure. The findings revealed that sulfuric acid had a more adverse effect on OPC concrete, resulting in a 26.6% reduction in the compressive strength, whereas fly ash and GLSS geopolymer concrete exhibited reductions of 10.9% and 7.3% in compressive strength, respectively. Also, Mehta and Siddique [124] exposed fly ash-based GPC to sulfuric acid, while OPC was employed as a fly ash substitute to raise the calcium content of the geopolymer system (0, 10, 20, and 30%). The samples were subjected to a solution of sulfuric acid at a concentration of 2% for 365 days before being assessed for deterioration based on the preserved compressive strength and weight loss. The findings of the study reveal that the samples with 0, 10, 20, and 30% OPC each gained 1.61, 2.34, 2.89, and 4.26% of their initial mass during the acid exposure. This is because the GPC specimens were cured in an oven for 24 h at 80 °C, producing more pores in the concrete matrix. These pores absorbed the sulfuric acid solution when the specimens were subjected to it, thereby increasing the resulting mass at an early age. However, as the exposure time increased, the mass loss increased, as shown in Figure 9.

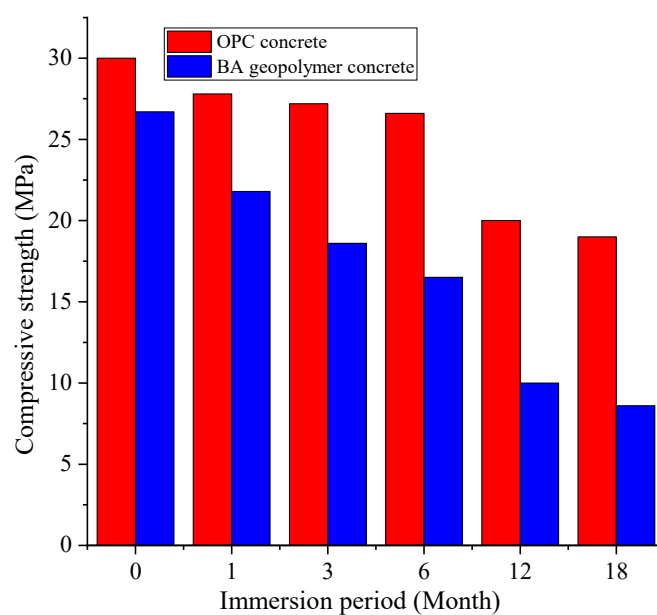


Figure 7. Compressive strengths of the concrete samples after being subjected to sulfuric acid [120].



Figure 8. Geopolymer specimens exposed to 2% sulfuric acid solution [111].

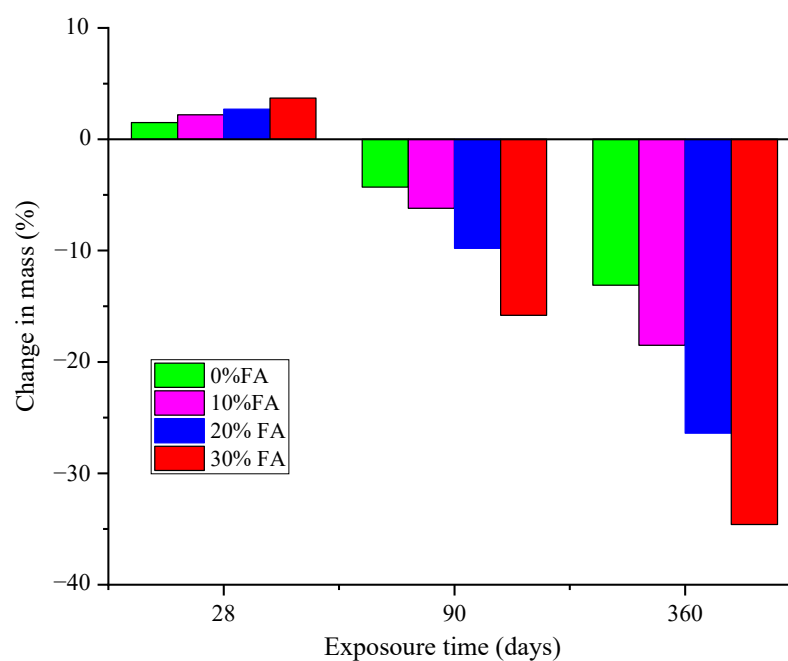


Figure 9. Mass losses of GPC samples subjected to a sulfuric acid solution [124].

Çevik et al. [125] examined whether nano-silica affected the GPC specimens' short-term severe durability performance. GPC and OPC concrete specimens were subjected to sulfuric acid concentrations of 5% (H_2SO_4) for 1 month, as shown in Figure 10. The surface erosion on the GPC specimens treated with H_2SO_4 solution was moderate, while the OPC specimens had severe surface erosion as a result of their greater CaO content. Likewise, Jena et al. [11] explored the properties of fly ash-based GPC with silica fume additions of 5%, 10%, and 15% by mass for long-term durability. In order to achieve this, concrete samples were subjected to corrosive chemical solutions containing 5% sodium chloride, 2% magnesium sulfate, and 2% sulfuric acid. The inclusion of silica fume in the GPC significantly enhanced its resistance to chemical attack. Additionally, blending silica fume and fly ash into GPC led to strength improvements and demonstrated positive performances in challenging environmental conditions. Moreover, Nnaemeka and Singh [126] investigated the effects of kaolin on fly ash-based GPC in 2% sulfuric acid by tracking variations in the weight and compressive strength, and the effects of acid exposure on the samples were evaluated. The results show that all the concrete samples experienced varying degrees of weight loss, with the loss increasing over time. Also, Alomayri et al. [127] evaluated GPC made from raw RHA and blast furnace slag (BFS). It has been observed that the raw RHA mixture, which replaced BFS by 10%, was more resistant to acid attack than the control mixture, which used BFS as the only precursor. Figure 11 illustrates the comparison between FA-GPC and PC concrete following 60-day acid immersion.



Figure 10. Specimens exposed to sulfuric acid [125].



Figure 11. FA-GPC and PC concrete samples submerged in acid for 60 days [115].

In conclusion, it has been shown that geopolymer concrete exhibits better chemical stability than OPC concrete because the geopolymerized bonding of the former is more resilient to deterioration caused by sulfuric acid than the Portland cementation bonding.

3.4. Sulfate Corrosion Resistance

Çevik et al. [125] evaluated the effect of nano-silica on the short-term durability performance of GPC composed of fly ash (FA-GPC) with conventional concrete. The

samples were subjected to solutions comprising seawater (NaCl), magnesium sulfate, and sulfuric acid (H_2SO_4) at concentrations of 0.5%, 1.5%, and 3.5%, respectively. The findings reveal that, due to their lower calcium content, FAGPC concrete exhibited superior resistance to chemical attacks compared with OPC concrete. The visual appearances of the specimens are shown in Figure 12a,b. Manhanpally et al. [99] demonstrated that the durability performance of GPC is unaffected by the inclusion of recycled particles. Nnaemeka and Singh [126] indicated how kaolin affected the durability of fly ash-based GPC when exposed to a solution of sodium sulfate at a 5% concentration. The results show that, in comparison to traditional OPC concrete, geopolymer concrete generally exhibited superior resistance to chemical deterioration. Likewise, Bellum et al. [128] investigated how long-lasting GPC compared to typical Portland cement concrete. GGBFS was integrated into FA, and the specimens were subjected to a solution of 5% salt sulfate. The results show that GPC outperformed standard concrete in terms of sodium sulfate resistance. Also, Chindaprasirt et al. [121] studied how the fineness of fly ash impacts the resistance to sulfate attacks and water requirements in hardened mortar. Their findings suggest that, except for coarse fly ash, all the fineness levels exhibited significant enhancements in sulfate resistance. Ziada et al. [129] examined the impact of bacterial healing on geopolymer concrete subjected to simultaneous exposures to sulfate and freeze–thaw conditions. Their findings provide a practical approach to crack repair in marine structures, dams, and buildings directly in contact with water. In order to enhance the mechanical properties and reduce the water absorption capacity of these structures, the use of bacterial solutions is recommended, particularly in regions near the cold sea where both sulfate and freeze–thaw effects are prevalent.

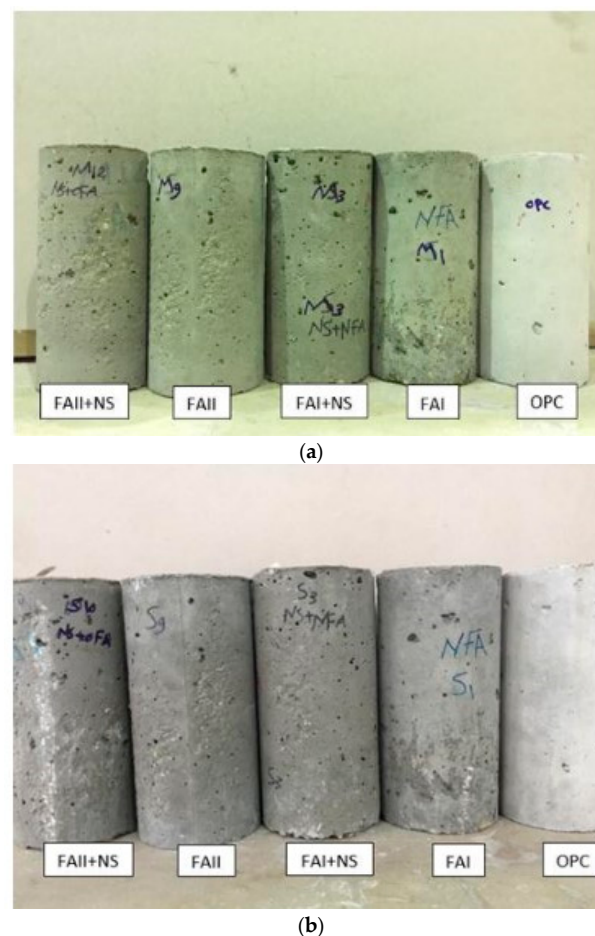


Figure 12. The visual appearances of the test specimens exposed for 30 days to chemical attack [125]: (a) samples subjected to magnesium sulfate, and (b) samples subjected to seawater.

It can be seen that GPC has a higher sulfate resistance than OPC concrete because of the stability of its cross-linked silicate gel compared to C–S–H gel. In contrast to the C–S–H gel in OPC concrete, which dissolves in sulfate solution and decalcifies to produce gypsum or ettringite, the structure of aluminosilicate gel is nearly insoluble in sulfate solution. However, the GPC breakdown mechanism varies slightly amongst different sulfate solutions, and GPC's sulfate resistance is greatly influenced by the alkali activator employed, the chemical makeup of the source material, and the curing environment.

3.5. Resistance to Sodium Chloride Solution

In coastal and waterfront areas, structures are particularly susceptible to extensive concrete corrosion due to processes involving ionic absorption and acidic reactions. One type of bad chemical penetration in concrete is a chloride attack, which happens when chloride ions get into the pore structure of the concrete through capillary action or hydrostatic pressure [130]. Generally, the ability to resist the penetration of chloride ions bears a resemblance to the capacity to withstand sulfate attack [13]. For instance, Çevik et al. [125] reported that exposing GPC and OPC specimens to seawater resulted in a weight increase for GPC after two weeks and one month, while OPC decreased after one month. In comparison, the compressive strengths of the OPC specimens decreased more than those of the GPC specimens. Referring to a study by Jena et al. [11], the presence of salt in the pores of the concrete matrix influenced the increase in specimen mass as a result of solution absorption. Although the compressive strength fell, the geopolymer specimens showed a strength that was about 65% greater than that of the Portland cement concrete specimens. Moreover, Bellum et al. [128] reported that GPC based on FA–GGBFS demonstrates superior resistance to the chloride solution. For both 30 and 60 days, the specimen surfaces were exposed to sodium chloride arrangements without any signs of deterioration. Furthermore, no significant difference in the compressive strengths was found, which indicates the high GPC use in construction in the marine zone. In research by Kumar et al. [131] involving submerging geopolymer and OPC concrete in a 5% salt chloride solution (seawater), the results reveal that the conventional OPC concrete specimens experienced more substantial mass loss compared to the GPC specimens, demonstrating that GPC specimens exhibit greater stability in seawater environments. Additionally, the GPC specimens showed greater strength than the traditional concrete specimens after 3 months of seawater immersion, although both continued to deteriorate after that time. These findings demonstrate that, in comparison to OPC concrete, the GPC specimens are more resistant chemically to NaCl solution.

This review observed that chloride resistance was directly correlated with GPC's capacity to bind with chloride ions and prevent their entry and diffusion throughout the body. The right alkali activator and improved curing conditions can lead to optimized pore structure, increased degree of polymerization, production of more N(C)–A–S–H gels capable of adsorbing free chloride ions, reduction in the amount of free chloride ions, and ultimately, improved chloride resistance of GPC.

3.6. Abrasion Resistance

Abrasion is a mechanical process that occurs when two surfaces meet, where one surface moves or slides against the other, and the other is exposed to friction, rubbing, or scraping. This interaction between the surfaces can lead to the removal of materials from either of the surfaces. It is considered one of the most important elements of the durability of concrete surface wear [132]. Compressive strength, aggregate toughness, and geopolymer binder hardness all generally influence the abrasion resistance of GPC [32]. Weight loss is a key aspect in determining abrasion resistance [13], and concrete can tolerate rubbing, wear and tear. Currently, the BS EN 1338:2003 [133], IS 1237-2021 [134], and ASTM standards (C-994-1999) [135] are being used to study the abrasion resistance of GPC [125]. For instance, Çevik et al. [125] assessed the pavement geopolymer concrete's durability and wear resistance in response to continuous traffic exposure by conducting an abrasion resistance test on slabs measuring 500 mm × 500 mm × 100 mm after 28 days of curing. The

findings revealed that the average abrasion on the upper surface was 1.08 mm, while the lower surface exhibited an average abrasion of 0.92 mm. Generally, the lower concrete layer displayed lower abrasion compared to the upper surface, primarily due to the superior compaction in the lower portion. According to Ramujee and Potharaju [136], the abrasion resistance of the GPC was higher than that of conventional OPC concretes. For a 12 h charge, the average depth of wear is 61% higher for OPC than for GPC, and 64% higher for a 24 h charge. Moreover, Wongsu et al. [137] examined the abrasion resistance of lightweight GPC incorporating natural limestone, pumice and clay brick aggregates and river sand. They observed that as the ratio of sodium silicate to sodium hydroxide increased in the GPC samples, the specimens' weight loss decreased. This observation was made regarding the extent of wear after 28 days. In another study by Luhar et al. [138], the abrasion resistance of high calcium fly ash GPC was investigated by changing the ratio of liquid alkaline to ash and varying the amounts of recycled asphaltic concrete aggregate (RACA). This study aimed to evaluate and contrast the OPC concrete abrasion resistance with rubberized GPC concrete. The findings suggest that by increasing the proportion of rubber fibers in the concrete samples, the wear depth diminished. The reduction in the wear depth was evident in samples fabricated from both concrete types, demonstrating that the inclusion of rubber fibers improved their abrasion resistance. Wongkvanklom et al. [139] reported that with the increasing quantity of recycled asphaltic concrete aggregate, the weight loss caused by surface abrasion in the GPC decreased. The addition of more recycled asphaltic concrete aggregate to the geopolymer concrete mix tends to reduce the pore space, leading to the most substantial enhancement of surface abrasion resistance. On this note, these results indicate that the addition of strong and less porous particles significantly improves the abrasion resistance of GPC. Also, Karaaslan et al. [140] replaced the calcium aluminate cement (CAC) by pumice comprising up to 20% of the entire powder binder, and they noted the enhanced abrasion resistance of geopolymer concretes (PGCs) made with 30 wt.% of FA and 70 wt.% of pumice. Regardless of the CAC replacement level, PGCs had superior abrasion resistance than OPC.

The review leads to the conclusion that the use of strong and less porous aggregates may be significantly aided in the creation of high abrasion resistance geopolymer concrete. In order to increase the abrasion resistance of geopolymer concrete, the usage of durable raw materials such as recycled granite and basalt aggregates is intriguing.

3.7. Freeze–Thaw Resistance

Concrete deterioration is caused by many freeze–thaw cycles and shows up as fractures, concrete peeling, and surface spalling. Cross-sectional cracking can happen under very severe freeze–thaw conditions, although surface damage is more common. Concrete walls, walkways, and other surfaces are especially prone to severe surface deterioration [141]. When concrete's tensile strength is exceeded, freezing at low temperatures may cause the microcracks to enlarge in size. When the cycles of freezing and thawing are over, the fissures gradually widen and expand, weakening the material [13]. To evaluate concrete's resistance to freeze–thaw conditions and estimate the surface peeling and spalling, various testing procedures and evaluation approaches are available. For example, Zhao et al. [142] assessed the freeze–thaw resistance involved evaluation of mass loss, changes in dynamic elasticity modulus, and compressive strength reduction. The results indicate that after five freeze–thaw cycles, GPC with 10% slag starts to deteriorate, despite high-temperature curing that could have increased its resistance to freeze–thaw cycling. Moreover, in comparison with the freeze–thaw resistance of OPC concrete, GPC containing 50% slag can endure 225 freeze–thaw cycles, while GPC containing 30% slag degraded after 50 freeze–thaw cycles. Pilehvar et al. [103] examined the influence of freeze–thaw cycles on the mechanical and physical characteristics of two dissimilar micro-encapsulated phase change materials (MPCM) in OPC concrete and GPC. Microscopic analysis revealed that freeze–thaw cycles could have a direct impact on the degradation of concrete because of the formation of microcracks in the weak interfacial transition zones between the cement paste and aggre-

gates or between the paste and MPCM. The inclusion of MPCM demonstrated remarkable resistance to freeze–thaw cycles with only a slight reduction in the compressive strength, in contrast to the samples without MPCM, which exhibited a more pronounced decrease. In a research study by Özdal et al. [141], ferrochrome slag (FS) and GGBFS were utilized as source materials in GPC mixtures activated by sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). Two distinct slag-based geopolymer concrete (SGC) mixtures were subjected to freeze–thaw (F–Z) cycles and examined by scanning electron microscopy (SEM) analysis. The results show that as the proportion of GGBFS in the SGC mix increased, the mechanical properties of the specimens were improved in terms of resistance to the F–T effect, and samples containing 100% FS and 75% FS disintegrated after 150 and 200 F–T cycles, respectively, as shown in Figure 13a–c. In addition, Zhang et al. [143] reported that regardless of the replacement proportion, the addition of crumb rubber (CR) increased the stiffness and freeze–thaw resilience of GPC. Compared with other concretes, 10% CR concrete exhibited reduced dimensions and fewer internal cracks. Additionally, CR possesses remarkable energy dissipation properties that can mitigate damage resulting from freeze–thaw cycles. In contrast, Kumar, et al. [131] found that as the number of freeze–thaw cycles increases, it has been observed that both GPC and traditional concrete specimens consistently experience mass loss. However, traditional concrete specimens demonstrated greater stability when subjected to freeze–thaw conditions. In addition, in comparison to GPC specimens, traditional concrete samples showed increases in the compressive strength following the freeze–thaw cycles, while both types of concrete continued to degrade.

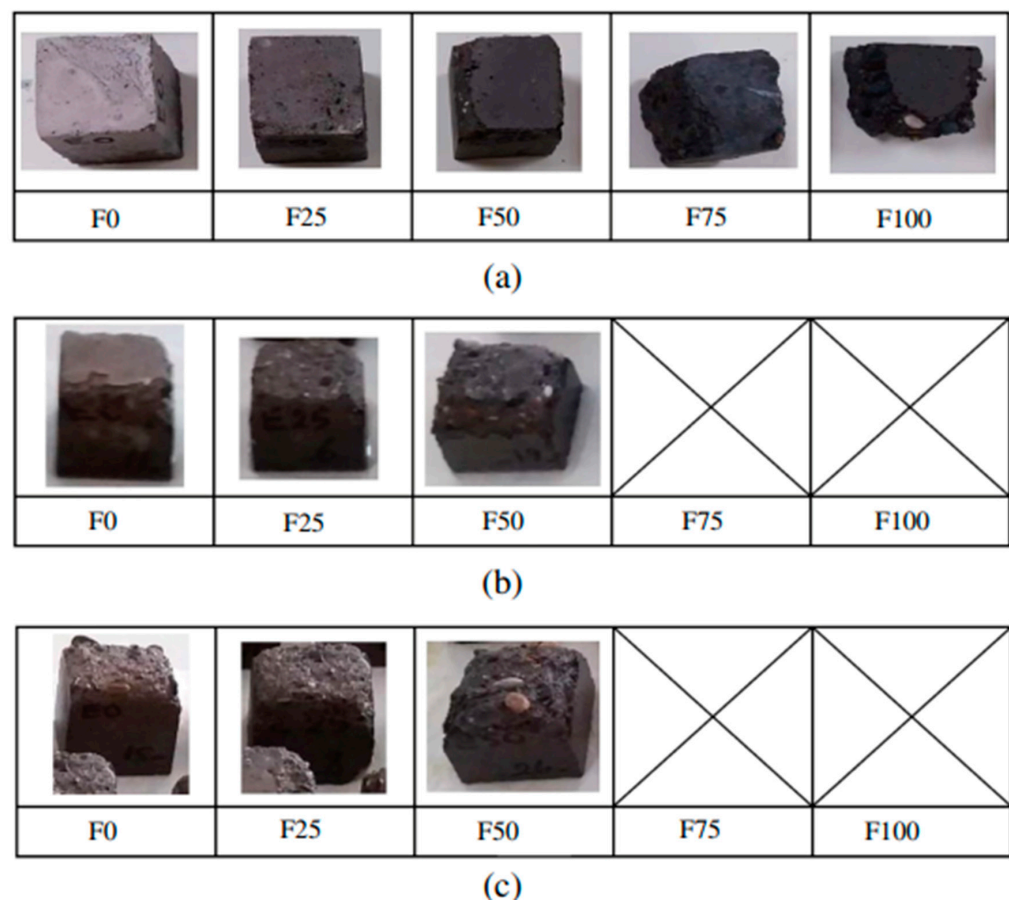


Figure 13. Appearances of the samples after (a) 100 freeze–thaw cycles, (b) 200 cycles, and (c) 300 cycles [141].

In freeze–thaw conditions, both the capillary absorption rate and degree of GPC saturation increase. This can be achieved by developing a dense pore structure and increasing

the degree of polymerization of the binder material, which, in turn, enhances the GPC's resistance to freeze–thaw cycles.

4. Conclusions and Future Recommendations

This review aims to offer an in-depth comprehension of the durability characteristics of geopolymer concrete. However, it is important to note that various factors influence the results obtained, making it challenging to arrive at conclusive decisions regarding the waste materials used in geopolymer concrete production. From the analysis and findings presented in this review, the following conclusions can be deduced.

- The review has shown promising outcomes and holds significant potential for mitigating carbon dioxide emissions, streamlining the recycling and repurposing of waste materials, and fostering the advancement of sustainability by incorporating industrial and agricultural byproducts to produce geopolymer concrete.
- As a material with better durability, geopolymer concrete is a more sustainable substitute and a more durable material for construction applications compared to conventional concrete.
- It is observed that geopolymer concrete exhibits greater chemical stability compared to OPC concrete owing to the enhanced durability of its geopolymerized bonding, which outperforms the Portland cement bonding in withstanding sulfuric acid deterioration.
- A high abrasion resistance might potentially be developed using geopolymer concrete that has dense and less porous aggregates.

The recommendations for further study may be summarized as follows.

- Further research should extend the exploration of geopolymer concrete resistance to acids by encompassing other types of acids, including carbonic and hydrochloric acids.
- It may be interesting to investigate the acid resistance of geopolymer concrete made from various aluminosilicate sources, such as volcanic ash, low-grade clay, bagasse ash, wood ash, etc.
- In the future, the longevity of GPC foundations and prefabricated structural components will need to be investigated.
- Geopolymer concrete can be used to make structural elements, although more research needs to be conducted to come up with more practical design suggestions. This will make it easier to use this material in the real world in the future.

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References

1. Ardhir, P.J.; Ardra, R.; Santhosh, P.P.; Sathyan, D. A review on structural performance of geopolymer beam and geopolymer for strengthening the beam. *Mater. Today Proc.* **2022**, *64*, 74–78. [\[CrossRef\]](#)
2. Rahemipoor, S.; Hasany, M.; Mehrali, M.; Almdal, K.; Ranjbar, N.; Mehrali, M. Phase change materials incorporation into 3D printed geopolymer cement: A sustainable approach to enhance the comfort and energy efficiency of buildings. *J. Clean. Prod.* **2023**, *417*, 138005. [\[CrossRef\]](#)
3. Pradhan, P.; Panda, S.; Parhi, S.K.S.; Panigrahi, S.K. Factors affecting production and properties of self-compacting geopolymer concrete—A review. *Constr. Build. Mater.* **2022**, *344*, 128174. [\[CrossRef\]](#)
4. Mo, K.H.; Alengaram, U.J.; Jumaat, M.Z. Structural performance of reinforced geopolymer concrete members: A review. *Constr. Build. Mater.* **2016**, *120*, 251–264. [\[CrossRef\]](#)

5. Palomo, A.; Monteiro, P.; Martauz, P.; Bilek, V.; Fernandez-Jimenez, A. Hybrid binders: A journey from the past to a sustainable future (opus caementicium futurum). *Cem. Concr. Res.* **2019**, *124*, 105829. [\[CrossRef\]](#)
6. Scrivener, K.L.; Nonat, A. Hydration of cementitious materials, present and future. *Cem. Concr. Res.* **2011**, *41*, 651–665. [\[CrossRef\]](#)
7. Scrivener, K.L.; John, V.M.; Gartner, E.M. Eco-efficient cements: Potential economically viable solutions for a low-CO₂ cement-based materials industry. *Cem. Concr. Res.* **2018**, *114*, 2–26. [\[CrossRef\]](#)
8. Bonen, D.; Tasdemir, M.A.; Sarkar, S.L. The evolution of cementitious materials through history. In *Proceeding of Materials Research Society Symposium*; Springer Nature: Berlin/Heidelberg, Germany, 1995; Volume 370, pp. 159–168.
9. Neville, A. Consideration of durability of concrete structures: Past, present, and future. *Mater. Struct. Mater. Constr.* **2001**, *34*, 114–118. [\[CrossRef\]](#)
10. Thomas, B.S.; Yang, J.; Bahurudeen, A.; Chinnu, S.N.; Abdalla, J.A.; Hawileh, R.A.; Hamada, H.M. Geopolymer concrete incorporating recycled aggregates: A comprehensive review. *Clean. Mater.* **2022**, *3*, 100056. [\[CrossRef\]](#)
11. Jena, S.; Panigrahi, R.; Sahu, P. Mechanical and durability properties of fly ash geopolymer concrete with silica fume. *J. Inst. Eng. India Ser. A* **2019**, *100*, 697–705. [\[CrossRef\]](#)
12. Abdalla, T.A.; Omer, E.I.I.; Khalifa, N.M.M.; Albasheir, M.A.A.; Abdulrajman, H.M.A.; Abdown, A.G.M. Effect of copper slag on workability and compressive strength of concrete. *Seybold Rep.* **2023**, *18*, 2657–2669. [\[CrossRef\]](#)
13. Zhang, P.; Sun, X.; Wang, F.; Wang, J. Mechanical properties and durability of geopolymer recycled aggregate concrete: A review. *Polymers* **2023**, *15*, 615. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Munir, Q.; Abdulkareem, M.; Horttanainen, M.; Kärki, T. A comparative cradle-to-gate life cycle assessment of geopolymer concrete produced from industrial side streams in comparison with traditional concrete. *Sci. Total Environ.* **2023**, *865*, 161230. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Abdalla, T.A.; Koteng, D.O.; Shitote, S.M.; Matallah, M. Mechanical and durability properties of concrete incorporating silica fume and a high volume of sugarcane bagasse ash. *Results Eng.* **2022**, *16*, 100666. [\[CrossRef\]](#)
16. Zakka, W.P.; Lim, N.H.A.S.; Khun, M.C. A scientometric review of geopolymer concrete. *J. Clean. Prod.* **2021**, *280*, 2021. [\[CrossRef\]](#)
17. Zeyad, A.M.; Magbool, H.M.; Tayeh, B.A.; de Azevedo, A.R.G.; Abutaleb, A.; Hussain, Q. Production of geopolymer concrete by utilizing volcanic pumice dust. *Case Stud. Constr. Mater.* **2022**, *16*, e00802. [\[CrossRef\]](#)
18. Peng, Y.; Unluer, C. Analyzing the mechanical performance of fly ash-based geopolymer concrete with different machine learning techniques. *Constr. Build. Mater.* **2022**, *316*, 125785. [\[CrossRef\]](#)
19. Hawileh, R.A.; Badrawi, H.A.; Makahleh, H.Y.; Karzad, A.S.; Abdalla, J.A. Behavior of reinforced concrete beams cast with a proposed geopolymer concrete (GPC) mix. *Int. J. Appl. Sci. Eng.* **2022**, *19*, 2022017. [\[CrossRef\]](#)
20. Sağır, M.A.; Karakoç, M.B.; Özcan, A.; Ekinci, E.; Yolcu, A. Effect of silica fume and waste rubber on the performance of slag-based geopolymer mortars under high temperatures. *Struct. Concr.* **2023**, *24*, 6690–6708. [\[CrossRef\]](#)
21. Jan, A.; Pu, Z.; Khan, I.; Khubaib, M. A comprehensive review on the effect of fibers on fresh and engineering properties of geopolymer concrete. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **2023**. [\[CrossRef\]](#)
22. Pham, D.Q.; Nguyen, T.N.; Le, S.T.; Pham, T.T.; Ngo, T.D. The structural behaviours of steel reinforced geopolymer concrete beams: An experimental and numerical investigation. *Structures* **2021**, *33*, 567–580. [\[CrossRef\]](#)
23. Kumar, B.S.C.; Ramesh, K. Analytical study on flexural behaviour of reinforced geopolymer concrete beams by ANSYS. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2018; Volume 455, p. 012065. [\[CrossRef\]](#)
24. Tran, T.M.; Trinh, H.T.M.K.; Nguyen, D.; Tao, Q.; Mali, S.; Pham, T.M. Development of sustainable ultra-high-performance concrete containing ground granulated blast furnace slag and glass powder: Mix design investigation. *Constr. Build. Mater.* **2023**, *397*, 132358. [\[CrossRef\]](#)
25. Khalaf, A.A.; Kopecko, K.; Merta, I. Prediction of the compressive strength of fly ash geopolymer concrete by an optimised neural network model. *Polymers* **2022**, *14*, 1423. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Abdalla, T.A.; Koteng, D.O.; Shitote, S.M.; Matallah, M. Mechanical properties of eco-friendly concrete made with sugarcane bagasse ash. *Civ. Eng. J.* **2022**, *8*, 1227–1239. [\[CrossRef\]](#)
27. Das, R.; Panda, S.; Sahoo, A.S.; Panigrahi, S.K. Effect of superplasticizer types and dosage on the flow characteristics of GGBFS based self-compacting geopolymer concrete. *Mater. Today Proc.* **2023**. [\[CrossRef\]](#)
28. Shen, P.; Han, P.; Guo, T.; Wang, R.; Song, W.; Bai, X.; Ma, F.; Wang, X.; He, B. Study on the Setting and Hardening Process of red mud-coal metakaolin geopolymer concrete by Electrochemical Impedance Spectroscopy. *Int. J. Electrochem. Sci.* **2022**, *17*, 221158. [\[CrossRef\]](#)
29. Le, H.B.; Bui, Q.B.; Tang, L. Geopolymer recycled aggregate concrete: From experiments to empirical models. *Materials* **2021**, *14*, 1180. [\[CrossRef\]](#)
30. Ahmed, H.Q.; Jaf, D.K.; Yaseen, S.A. Flexural capacity and behaviour of geopolymer concrete beams reinforced with glass fibre-reinforced polymer bars. *Int. J. Concr. Struct. Mater.* **2020**, *14*, 14. [\[CrossRef\]](#)
31. Zeini, H.A.; Al-Jeznawi, D.; Imran, H.; Bernardo, L.F.A.; Al-Khafaji, Z.; Ostrowski, K.A. Random forest algorithm for the strength prediction of geopolymer stabilized clayey soil. *Sustainability* **2023**, *15*, 1408. [\[CrossRef\]](#)
32. Wong, L.S. Durability performance of geopolymer concrete: A review. *Polymers* **2022**, *14*, 868. [\[CrossRef\]](#)

33. Sherwani, A.F.H.; Younis, K.H.; Arndt, R.W.; Pilakoutas, K. Performance of self-compacted geopolymer concrete containing fly ash and slag as binders. *Sustainability* **2020**, *14*, 15063. [\[CrossRef\]](#)
34. Li, L.; Tao, Y.; Zhuang, E.; Cui, X.; Yu, K.; Yu, B.; Boluk, Y.; Bindiganavile, V.; Chen, Z.; Yi, C. Optimal amorphous oxide ratios and multifactor models for binary geopolymers from metakaolin blended with substantial sugarcane bagasse ash. *J. Clean. Prod.* **2022**, *377*, 134215. [\[CrossRef\]](#)
35. Li, W.; Shumuye, E.D.; Tang, S.; Wang, Z.; Zerfu, K. Eco-friendly fibre reinforced geopolymer concrete: A critical review on the microstructure and long-term durability properties. *Case Stud. Constr. Mater.* **2022**, *16*, e00894. [\[CrossRef\]](#)
36. Mabroum, S.; Moukannaa, S.; El Machi, A.; Taha, Y.; Benzaazoua, M.; Hakkou, R. Mine wastes based geopolymers: A critical review. *Clean. Eng. Technol.* **2020**, *1*, 100014. [\[CrossRef\]](#)
37. Kishore, K.; Pandey, A.; Wagri, N.K.; Saxena, A.; Patel, J.; Al-Fakih, A. Technological challenges in nanoparticle-modified geopolymer concrete: A comprehensive review on nanomaterial dispersion, characterization techniques and its mechanical properties. *Case Stud. Constr. Mater.* **2023**, *19*, e02265. [\[CrossRef\]](#)
38. Pham, T.-T.; Nguyen, N.-L.; Nguyen, T.-T.; Nguyen, T.-T.; Pham, T.-H. Effects of superplasticizer and water–binder ratio on mechanical properties of one-part alkali-activated geopolymer concrete. *Buildings* **2023**, *13*, 1835. [\[CrossRef\]](#)
39. Rehman, S.K.U.; Imtiaz, L.; Aslam, F.; Khan, M.K.; Haseeb, M.; Javed, M.F.; Alyousef, R.; Alabduljabbar, H. Experimental investigation of NaOH and KOH mixture in SCBA-based geopolymer cement composite. *Materials* **2020**, *13*, 3437. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Ahmed, H.U.; Mohammed, A.S.; Faraj, R.H.; Qaidi, S.M.A.; Mohammed, A.A. Compressive strength of geopolymer concrete modified with nano-silica: Experimental and modeling investigations. *Case Stud. Constr. Mater.* **2022**, *16*, e01036. [\[CrossRef\]](#)
41. Ali, A.H.M.; Abdalla, T.A.; Al Haqq, A.; Umar, A.; Mouhoumed, I.H.; Mohamed, I.A.R. Cost and time control in construction projects: A case study of Khartoum State. *Jilin Daxue Xuebao Gongxueban J. Jilin Univ. Eng. Technol. Ed.* **2020**, *41*, 184–194. [\[CrossRef\]](#)
42. Pasupathy, K.; Ramakrishnan, S.; Sanjayan, J. 3D concrete printing of eco-friendly geopolymer containing brick waste. *Cem. Concr. Compos.* **2023**, *138*, 104943. [\[CrossRef\]](#)
43. Shilar, F.A.; Ganachari, S.V.; Patil, V.B.; Khan, T.M.Y.; Javed, S.; Baig, R.U. Optimization of alkaline activator on the strength properties of geopolymer concrete. *Polymers* **2022**, *14*, 2434. [\[CrossRef\]](#)
44. Al Banna, W.N.; Poloju, K.K. Study on characteristics of geopolymer concrete. In *Recent Advances in Civil Engineering—Lecture Notes in Civil Engineering*; Springer Nature: Berlin/Heidelberg, Germany, 2022; Chapter 44, pp. 539–551. [\[CrossRef\]](#)
45. Hassan, A.; Arif, M.; Shariq, M. Use of geopolymer concrete for a cleaner and sustainable environment—A review of mechanical properties and microstructure. *J. Clean. Prod.* **2019**, *223*, 704–728. [\[CrossRef\]](#)
46. Mortar, N.A.M.; Al Bakri Abdullah, M.M.; Hussin, K.; Razak, R.A.; Hamat, S.; Hilmi, A.H.; Shahedan, N.N.; Li, L.Y.; Aziz, I.H.A. Finite element analysis on structural behaviour of Geopolymer reinforced concrete beam using Johnson-Cook damage in ABAQUS. *Arch. Metall. Mater* **2022**, *67*, 1349–1354. [\[CrossRef\]](#)
47. Mohanram, B.B.K.; Kanagavel, R. Effect of metakaolin on mechanical properties and flexural behavior of geopolymer-reinforced concrete beams. *Pract. Period. Struct. Des. Constr.* **2022**, *27*, 04022021. [\[CrossRef\]](#)
48. Parathi, S.; Nagarajan, P.; Pallikkara, S.A. Ecofriendly geopolymer concrete: A comprehensive review. *Clean Technol. Environ. Policy* **2021**, *23*, 1701–1713. [\[CrossRef\]](#)
49. Luhar, S.; Nicolaides, D.; Luhar, I. Fire resistance behaviour of geopolymer concrete: An overview. *Buildings* **2021**, *11*, 82. [\[CrossRef\]](#)
50. Singh, B.K.; Kumar, R.; Sengupta, S. Industrial production of fly ash and sand-based geopolymer bricks using different molarity of NaOH solution, and assessment of their mechanical and durability properties. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **2023**. [\[CrossRef\]](#)
51. Hosseinbor, J.; Madani, H.; Norouzifar, M.N. Improving the characteristics of less active geopolymer binders utilizing ground granulated blast-furnace slag under different curing conditions. *Sustainability* **2023**, *15*, 12165. [\[CrossRef\]](#)
52. Clausi, M.; Tarantino, S.C.; Magnani, L.L.; Riccardi, M.P.; Tedeschi, C.; Zema, M. Metakaolin as a precursor of materials for applications in Cultural Heritage: Geopolymer-based mortars with ornamental stone aggregates. *Appl. Clay Sci.* **2016**, *132–133*, 589–599. [\[CrossRef\]](#)
53. Komnitsas, K.; Zaharaki, D. Geopolymerisation: A review and prospects for the minerals industry. *Miner. Eng.* **2007**, *20*, 1261–1277. [\[CrossRef\]](#)
54. Bellum, R.R.; Muniraj, K.; Madduru, S.R.C. Influence of activator solution on microstructural and mechanical properties of geopolymer concrete. *Materialia* **2020**, *10*, 100659. [\[CrossRef\]](#)
55. Moradikhrou, A.B.; Safedian, M.; Golafshani, E.M. High-strength geopolymer concrete based on coal washing waste. *Constr. Build. Mater.* **2023**, *362*, 129675. [\[CrossRef\]](#)
56. Shilar, F.A.; Ganachari, S.V.; Patil, V.B.; Khan, T.M.Y.; Khadar, S.D.A. Molarity activity effect on mechanical and microstructure properties of geopolymer concrete: A review. *Case Stud. Constr. Mater.* **2022**, *16*, e01014. [\[CrossRef\]](#)
57. Amran, Y.H.M.; Alyousef, R.; Alabduljabbar, H.; El-Zeadani, M. Clean production and properties of geopolymer concrete: A review. *J. Clean. Prod.* **2020**, *251*, 119679. [\[CrossRef\]](#)

58. Kalaivani, M.; Shyamala, G.; Ramesh, S.; Angusenthil, K.; Jagadeesan, R. Performance evaluation of fly ash/slag based geopolymer concrete beams with addition of lime. *Mater. Today Proc.* **2020**, *27*, 652–656. [\[CrossRef\]](#)
59. Nuaklong, P.; Sata, V.; Wongsu, A.; Srinavin, K.; Chindaprasirt, P. Recycled aggregate high calcium fly ash geopolymer concrete with inclusion of OPC and nano-SiO₂. *Constr. Build. Mater.* **2018**, *174*, 244–252. [\[CrossRef\]](#)
60. Darmawan, M.S. Comparative study of flexural performance of geopolymer and Portland cement concrete beam using finite element analysis. *Int. J. Geomate* **2022**, *23*, 1–9. [\[CrossRef\]](#)
61. Poloju, K.K.; Srinivasu, K. Impact of GGBS and strength ratio on mechanical properties of geopolymer concrete under ambient curing and oven curing. *Mater. Today Proc.* **2021**, *42*, 962–968. [\[CrossRef\]](#)
62. Olivia, M.; Nikraz, H. Properties of fly ash geopolymer concrete designed by Taguchi method. *Mater. Des.* **2012**, *36*, 191–198. [\[CrossRef\]](#)
63. Thumrongvut, J.; Seangatith, S.; Phetchuay, C.; Suksiripattanapong, C. Comparative experimental study of sustainable reinforced Portland cement concrete and geopolymer concrete beams using rice husk ash. *Sustainability* **2022**, *14*, 9856. [\[CrossRef\]](#)
64. Tahwia, A.M.; Heniegal, A.M.; Abdellatif, M.; Tayeh, B.A.; Elrahman, M.A. Properties of ultra-high performance geopolymer concrete incorporating recycled waste glass. *Case Stud. Constr. Mater.* **2022**, *17*, e01393. [\[CrossRef\]](#)
65. Mashri, M.O.M.; Johari, M.A.M.; Ahmad, Z.A.; Mijarsh, M.J.A. Enhancing the properties of UPOFA-based geopolymer mortar via the incorporation of eggshell ash and silica fume. *J. Build. Eng.* **2023**, *65*, 105677. [\[CrossRef\]](#)
66. Kavipriya, S.; Dhavashankaran, D.; Ramkumar, S.; Lingeshwaran, N.; Deepanraj, C.G. Flexural strength characteristics of high performance geopolymer concrete using ceramic waste aggregates and silica fume. *Mater. Today Proc.* **2022**, *62*, 6879–6883. [\[CrossRef\]](#)
67. D'Elia, A.; Clausi, M.; Fernández-Jiménez, A.; Palomo, A.; Eramo, G.; Laviano, R.; Pinto, D. Alkali-activated binary binders with carbonate-rich Illitic clay. *Polymers* **2023**, *15*, 362. [\[CrossRef\]](#) [\[PubMed\]](#)
68. El Khomsi, A.; Ghaezouni, A.; Kandri, N.I.; Zerouale, A.; Rossignol, S. Moroccan clays for potential use as aluminosilicate precursors for geopolymer synthesis. *E3S Web Conf.* **2021**, *240*, 03001. [\[CrossRef\]](#)
69. Khalifa, A.Z.; Cizer, Ö.; Pontikes, Y.; Heath, A.; Patureau, P.; Bernal, S.A.; Marsh, A.T.M. Advances in alkali-activation of clay minerals. *Cem. Concr. Res.* **2020**, *132*, 106050. [\[CrossRef\]](#)
70. Valentini, L.; Contessi, S.; Dalconi, M.C.; Zorzi, F.; Garbin, E. Alkali-activated calcined smectite clay blended with waste calcium carbonate as a low-carbon binder. *J. Clean. Prod.* **2018**, *184*, 41–49. [\[CrossRef\]](#)
71. Migunthanna, J.; Rajeev, P.; Sanjayan, J. Waste clay brick as a part binder for pavement grade geopolymer concrete. *Int. J. Pavement Res. Technol.* **2023**. [\[CrossRef\]](#)
72. Fořt, J.; Mildner, M.; Keppert, M.; Pommer, V.; Černý, R. Experimental and environmental analysis of high-strength geopolymer based on waste bricks and blast furnace slag. *Polymers* **2023**, *15*, 3092. [\[CrossRef\]](#)
73. Babu, T.; Thangaraj, S. A novel approach for the synthesis of eco-friendly geopolymer ternary blended mortar with GGBS, sugarcane bagasse ash, and sewage sludge ash under ambient curing conditions. *KSCE J. Civ. Eng.* **2023**, *27*, 3441–3454. [\[CrossRef\]](#)
74. Venyite, P.; Makone, E.C.; Kaze, C.R.; Nana, A.; Nemaleu, J.G.D.; Kamseu, E.; Melo, U.C.; Leonelli, C. Effect of combined metakaolin and basalt powder additions to laterite-based geopolymers activated by rice husk ash (RHA)/NaOH solution. *Silicon* **2021**, *14*, 1643–1662. [\[CrossRef\]](#)
75. Huiskes, D.M.A.; Keulen, A.; Yu, Q.L.; Brouwers, H.J.H. Design and performance evaluation of ultra-lightweight geopolymer concrete. *Mater. Des.* **2016**, *89*, 516–526. [\[CrossRef\]](#)
76. Al Bakri, A.M.M.; Kamarudin, H.; Bnhussain, M.; Nizar, I.K.; Mastura, W.I.W. Mechanism and chemical reaction of fly ash geopolymer cement—A review. *J. Asian Sci. Res.* **2011**, *1*, 247–253.
77. Arunachalam, N.; Maheswaran, J.; Chellapandian, M.; Ozbakkaloglu, T. Effective utilization of copper slag for the production of geopolymer concrete with different NaOH molarity under ambient curing conditions. *Sustainability* **2022**, *14*, 16300. [\[CrossRef\]](#)
78. Amin, M.; Elsakhawy, Y.; El-Hassan, K.A.; Abdelsalam, B.A. Behavior evaluation of sustainable high strength geopolymer concrete based on fly ash, metakaolin, and slag. *Case Stud. Constr. Mater.* **2022**, *16*, e00976. [\[CrossRef\]](#)
79. Siddique, R.; Singh, M.; Jain, M. Recycling copper slag in steel fibre concrete for sustainable construction. *J. Clean. Prod.* **2020**, *271*, 122559. [\[CrossRef\]](#)
80. Al-Jabri, K.S.; Hisada, M.; Al-Oraimi, S.K.; Al-Saidy, A.H. Copper slag as sand replacement for high performance concrete. *Cem. Concr. Compos.* **2009**, *31*, 483–488. [\[CrossRef\]](#)
81. Wu, W.; Zhang, W.; Ma, G. Optimum content of copper slag as a fine aggregate in high strength concrete. *Mater. Des.* **2010**, *31*, 2878–2883. [\[CrossRef\]](#)
82. Chithra, S.; Kumar, S.R.R.S.; Chinnaraju, K. The effect of Colloidal Nano-silica on workability, mechanical and durability properties of High Performance Concrete with Copper slag as partial fine aggregate. *Constr. Build. Mater.* **2016**, *113*, 794–804. [\[CrossRef\]](#)
83. Al-Jabri, K.S.; Hisada, M.; Al-Saidy, A.H.; Al-Oraimi, S.K. Performance of high strength concrete made with copper slag as a fine aggregate. *Constr. Build. Mater.* **2009**, *23*, 2132–2140. [\[CrossRef\]](#)
84. Davidovits, J. Geopolymers and geopolymeric materials. *J. Therm. Anal.* **1989**, *35*, 429–441. [\[CrossRef\]](#)

85. Nagajothi, S.; Elavenil, S.; Angalaeswari, S.; Natrayan, L.; Mammo, W.D.; Jaya, R.P. Durability studies on fly ash based geopolymer concrete incorporated with slag and alkali solutions. *Adv. Civ. Eng.* **2022**, *2022*, 196446. [\[CrossRef\]](#)
86. Dinh, H.L.; Doh, J.-H.; Liu, J.; Lu, L.; Song, H.; Park, D. Comprehensive assessment of geopolymer concrete mechanical and environmental performance with glass cullet fine aggregates. *J. Build. Eng.* **2023**, *76*, 107094. [\[CrossRef\]](#)
87. Gupta, N.; Gupta, A.; Saxena, K.K.; Shukla, A.; Goyal, S.K. Mechanical and durability properties of geopolymer concrete composite at varying superplasticizer dosage. *Mater. Today Proc.* **2021**, *44*, 12–16. [\[CrossRef\]](#)
88. Moghaddam, S.C.; Madandoust, R.; Jamshidi, M.; Nikbin, I.M. Mechanical properties of fly ash-based geopolymer concrete with crumb rubber and steel fiber under ambient and sulfuric acid conditions. *Constr. Build. Mater.* **2021**, *281*, 122571. [\[CrossRef\]](#)
89. Xu, W.; Tang, Z.; Song, Y.; Xie, Y.; Lei, B.; Yu, H.; Long, G.; Kai, M. Drying shrinkage of geopolymeric recycled aggregate concrete. *Constr. Build. Mater.* **2023**, *395*, 132220. [\[CrossRef\]](#)
90. Tran, M.V.; Vu, T.H.; Nguyen, T.H.Y. Simplified assessment for one-part 3D-printable geopolymer concrete based on slump and slump flow measurements. *Case Stud. Constr. Mater.* **2023**, *18*, e01889. [\[CrossRef\]](#)
91. Poloju, K.K.; Srinivasu, K. The method for determining the effect of binder ratio and different curing methods on strength parameters of geopolymer concrete. *Jilin Daxue Xuebao Gongxueban J. Jilin Univ. Eng. Technol. Ed.* **2022**, *41*. [\[CrossRef\]](#)
92. Kutlusoy, E.; Maras, M.M.; Ekinci, E.; Rihawi, B. Production parameters of novel geopolymer masonry mortar in heritage buildings: Application in masonry building elements. *J. Build. Eng.* **2023**, *76*, 107038. [\[CrossRef\]](#)
93. Jaji, M.B.; Ibrahim, K.A.; van Zijl, G.P.A.G.; Babafemi, A.J. Effect of anisotropy on permeability index and water absorption of 3D printed metakaolin-based geopolymer concrete. *Mater. Today Proc.* **2023**. [\[CrossRef\]](#)
94. Wang, J.; Chen, X.; Li, C.; Zhou, Z.; Du, P.; Zhang, X. Evaluating the effect of kaliophilite on the fire resistance of geopolymer concrete. *J. Build. Eng.* **2023**, *75*, 106975. [\[CrossRef\]](#)
95. Chowdhury, S.; Mohapatra, S.; Gaur, A.; Dwivedi, G.; Soni, A. Study of various properties of geopolymer concrete—A review. *Mater. Today Proc.* **2021**, *46*, 5687–5695. [\[CrossRef\]](#)
96. Podolsky, Z.; Liu, J.; Dinh, H.; Doh, J.H.; Guerrieri, M.; Fragomeni, S. State of the art on the application of waste materials in geopolymer concrete. *Case Stud. Constr. Mater.* **2021**, *15*, e00637. [\[CrossRef\]](#)
97. Hassan, A.; Arif, M.; Shariq, M.; Alomayri, T. Experimental test and finite element modelling prediction on geopolymer concrete beams subject to flexural loading. *Innov. Infrastruct. Solut.* **2021**, *7*, 13. [\[CrossRef\]](#)
98. Zhang, H.Y.; Kodur, V.; Wu, B.; Yan, J.; Yuan, Z.S. Effect of temperature on bond characteristics of geopolymer concrete. *Constr. Build. Mater.* **2018**, *163*, 277–285. [\[CrossRef\]](#)
99. Manhanpally, N.; Nagarajan, P.; Saha, S.; Raja, I.Y. Mechanical and durability characteristics of GGBS-Dolomite geopolymer concrete using recycled coarse aggregates. *Mater. Today Proc.* **2023**. [\[CrossRef\]](#)
100. Almutairi, A.L.; Tayeh, B.A.; Adesina, A.; Isleem, H.F.; Zeyad, A.M. Potential applications of geopolymer concrete in construction: A review. *Case Stud. Constr. Mater.* **2021**, *15*, e00733. [\[CrossRef\]](#)
101. Dao, D.V.; Ly, H.B.; Trinh, S.H.; Le, T.T.; Pham, B.T. Artificial intelligence approaches for prediction of compressive strength of geopolymer concrete. *Materials* **2019**, *12*, 983. [\[CrossRef\]](#)
102. Un, C.H.; Sanjayan, J.G.; Nicolas, R.S.; van Deventer, J.S.J. Predictions of long-term deflection of geopolymer concrete beams. *Constr. Build. Mater.* **2015**, *94*, 10–19. [\[CrossRef\]](#)
103. Pilehvar, S.; Szczotok, A.M.; Rodríguez, J.F.; Valentini, L.; Lanzón, M.; Pamies, R.; Kjøniksen, A.-L. Effect of freeze-thaw cycles on the mechanical behavior of geopolymer concrete and Portland cement concrete containing micro-encapsulated phase change materials. *Constr. Build. Mater.* **2019**, *200*, 94–103. [\[CrossRef\]](#)
104. Li, N.; Shi, C.; Zhang, Z.; Wang, H.; Liu, Y. A review on mixture design methods for geopolymer concrete. *Compos. Part B Eng.* **2019**, *178*, 107490. [\[CrossRef\]](#)
105. Manikandan, P.; Selija, K.; Vasugi, V.; Kumar, V.P.; Natrayan, L.; Santhi, M.H.; Kumaran, G.S. An artificial neural network based prediction of mechanical and durability characteristics of sustainable geopolymer composite. *Adv. Civ. Eng.* **2022**, *2022*, 9343330. [\[CrossRef\]](#)
106. Van Roosmale, S.; De Kock, T.; Blom, J. Metakaolin-based geopolymers for stone conservation: Preliminary results on alkaline activation. *Adv. Geosci.* **2023**, *58*, 149–156. [\[CrossRef\]](#)
107. Occhipinti, R.; Strosio, A.; Finocchiaro, C.; Fugazzotto, M.; Leonelli, C.; Lo Faro, M.J.; Megna, B.; Barone, G.; Mazzoleni, P. Alkali activated materials using pumice from the Aeolian Islands (Sicily, Italy) and their potentiality for cultural heritage applications: Preliminary study. *Constr. Build. Mater.* **2020**, *259*, 120391. [\[CrossRef\]](#)
108. Ricciotti, L.; Molino, A.; Roviello, V.; Chianese, E.; Cennamo, P.; Roviello, G. Geopolymer composites for potential applications in cultural heritage. *Environments* **2017**, *4*, 91. [\[CrossRef\]](#)
109. Zaid, O.; Sor, N.A.H.; Martínez-García, R.; De Prado-Gil, J.; Elhadi, K.M.; Yosri, A.M. Sustainability evaluation, engineering properties and challenges relevant to geopolymer concrete modified with different nanomaterials: A systematic review. *Ain Shams Eng. J.* **2023**, 102373. [\[CrossRef\]](#)
110. Singh, B.; Ishwarya, G.; Gupta, M.; Bhattacharyya, S.K. Geopolymer concrete: A review of some recent developments. *Constr. Build. Mater.* **2015**, *85*, 78–90. [\[CrossRef\]](#)
111. Lavanya, G.; Jegan, J. Durability study on high calcium fly ash based geopolymer concrete. *Adv. Mater. Sci. Eng.* **2015**, *2015*, 731056. [\[CrossRef\]](#)

112. Saloni, Parveen; Lim, Y.Y.; Pham, T.M. Influence of Portland cement on performance of fine rice husk ash geopolymer concrete: Strength and permeability properties. *Constr. Build. Mater.* **2021**, *300*, 124321. [\[CrossRef\]](#)
113. Provis, J.L.; Myers, R.J.; White, C.E.; Rose, V.; Van Deventer, J.S. X-ray microtomography shows pore structure and tortuosity in alkali-activated binders. *Cem. Concr. Res.* **2012**, *42*, 855–864. [\[CrossRef\]](#)
114. Mansourghanaei, M.; Biklaryan, M.; Mardookhpour, A. Experimental study of the effects of adding silica nanoparticles on the durability of geopolymer concrete. *Aust. J. Civ. Eng.* **2022**, 1–13. [\[CrossRef\]](#)
115. Ojha, A.; Aggarwal, P. Durability performance of low calcium Flyash-Based geopolymer concrete. *Structures* **2023**, *54*, 956–963. [\[CrossRef\]](#)
116. Adam, A.A.; Deviana, L.; Siregar, A.P.N. Water absorption of ambient-cured geopolymer concrete. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1157*, 012015. [\[CrossRef\]](#)
117. Abbass, M.; Singh, G. Experimental investigation of engineered alkali-activated fibrous geopolymer concrete. *J. Build. Pathol. Rehabil.* **2022**, *8*, 12. [\[CrossRef\]](#)
118. Luhar, S.; Chaudhary, S.; Luhar, I. Thermal resistance of fly ash based rubberized geopolymer concrete. *J. Build. Eng.* **2018**, *19*, 420–428. [\[CrossRef\]](#)
119. Okoye, F.N.; Prakash, S.; Singh, N.B. Durability of fly ash based geopolymer concrete in the presence of silica fume. *J. Clean. Prod.* **2017**, *149*, 1062–1067. [\[CrossRef\]](#)
120. Ariffin, M.A.M.; Bhutta, M.A.R.; Hussin, M.W.; Tahir, M.M.; Aziah, N. Sulfuric acid resistance of blended ash geopolymer concrete. *Constr. Build. Mater.* **2013**, *43*, 80–86. [\[CrossRef\]](#)
121. Chindaprasirt, P.; Homwuttiwong, S.; Sirivivatnanon, V. Influence of fly ash fineness on strength, drying shrinkage and sulfate resistance of blended cement mortar. *Cem. Concr. Res.* **2004**, *34*, 1087–1092. [\[CrossRef\]](#)
122. Bakharev, T. Resistance of geopolymer materials to acid attack. *Cem. Concr. Res.* **2005**, *35*, 658–670. [\[CrossRef\]](#)
123. Albitar, M.; Ali, M.S.M.; Visintin, P.; Drechsler, M. Durability evaluation of geopolymer and conventional concretes. *Constr. Build. Mater.* **2017**, *136*, 374–385. [\[CrossRef\]](#)
124. Mehta, A.; Siddique, R. Sulfuric acid resistance of fly ash based geopolymer concrete. *Constr. Build. Mater.* **2017**, *146*, 136–143. [\[CrossRef\]](#)
125. Çevik, A.; Alzebaree, R.; Humur, G.; Niş, A.; Gülşan, M.E. Effect of nano-silica on the chemical durability and mechanical performance of fly ash based geopolymer concrete. *Ceram. Int.* **2018**, *44*, 12253–12264. [\[CrossRef\]](#)
126. Nnaemeka, O.F.; Singh, N.B. Durability properties of geopolymer concrete made from fly ash in presence of Kaolin. *Mater. Today Proc.* **2020**, *29*, 781–784. [\[CrossRef\]](#)
127. Alomayri, T.; Adesina, A.; Das, S. Influence of amorphous raw rice husk ash as precursor and curing condition on the performance of alkali activated concrete. *Case Stud. Constr. Mater.* **2021**, *15*, e00777. [\[CrossRef\]](#)
128. Bellum, R.R.; Muniraj, K.; Madduru, S.R.C. Exploration of mechanical and durability characteristics of fly ash-GGBFS based green geopolymer concrete. *SN Appl. Sci.* **2020**, *2*, 919. [\[CrossRef\]](#)
129. Ziada, M.; Tanyildizi, H.; Uysal, M. Bacterial healing of geopolymer concrete exposed to combined sulfate and freeze-thaw effects. *Constr. Build. Mater.* **2023**, *369*, 130517. [\[CrossRef\]](#)
130. Masoule, M.S.T.; Bahrami, N.; Karimzadeh, M.; Mohasanati, B.; Shoaee, P.; Ameri, F.; Ozbakkaloglu, T. Lightweight geopolymer concrete: A critical review on the feasibility, mixture design, durability properties, and microstructure. *Ceram. Int.* **2022**, *48*, 10347–10371. [\[CrossRef\]](#)
131. Kumar, R.; Verma, M.; Dev, N. Investigation on the effect of seawater condition, sulphate attack, acid attack, freeze–thaw condition, and wetting–drying on the geopolymer concrete. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **2022**, *46*, 2823–2853. [\[CrossRef\]](#)
132. Lau, C.K.; Lee, H.; Vimonsatit, V.; Huen, W.Y.; Chindaprasirt, P. Abrasion resistance behaviour of fly ash based geopolymer using nanoindentation and artificial neural network. *Constr. Build. Mater.* **2019**, *212*, 635–644. [\[CrossRef\]](#)
133. BS EN 1338:2003; Concrete Paving Blocks—Requirements and Test Methods. The British Standards (BSI) and The European Standard (CEN): London, UK, 2003.
134. IS 1237-2021; Cement Concrete Flooring Tiles—Specification. Bureau of Indian Standards: New Delhi, India, 2021.
135. ASTM C 944/C 944M–99; Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method. ASTM International: Conshohocken, PA, USA, 2005.
136. Ramujee, K.; Potharaju, M. Abrasion resistance of geopolymer composites. *Procedia Mater. Sci.* **2014**, *6*, 1961–1966. [\[CrossRef\]](#)
137. Wongsu, A.; Sata, V.; Nuaklong, P.; Chindaprasirt, P. Use of crushed clay brick and pumice aggregates in lightweight geopolymer concrete. *Constr. Build. Mater.* **2018**, *188*, 1025–1034. [\[CrossRef\]](#)
138. Luhar, S.; Chaudhary, S.; Luhar, I. Development of rubberized geopolymer concrete: Strength and durability studies. *Constr. Build. Mater.* **2019**, *204*, 740–753. [\[CrossRef\]](#)
139. Wongkvanklom, A.; Posi, P.; Kampala, A.; Kaewngao, T.; Chindaprasirt, P. Beneficial utilization of recycled asphaltic concrete aggregate in high calcium fly ash geopolymer concrete. *Case Stud. Constr. Mater.* **2021**, *15*, e00615. [\[CrossRef\]](#)
140. Karaaslan, C.; Yener, E.; Bağatur, T.; Polat, R. Improving the durability of pumice-fly ash based geopolymer concrete with calcium aluminate cement. *J. Build. Eng.* **2022**, *59*, 105110. [\[CrossRef\]](#)
141. Özdal, M.; Karakoç, M.B.; Özcan, A. Investigation of the properties of two different slag-based geopolymer concretes exposed to freeze–thaw cycles. *Struct. Concr.* **2019**, *22*, E332–E340. [\[CrossRef\]](#)

142. Zhao, R.; Yuan, Y.; Cheng, Z.; Wen, Y.; Li, J.; Li, F.; Ma, Z.J. Freeze-thaw resistance of Class F fly ash-based geopolymer concrete. *Constr. Build. Mater.* **2019**, *222*, 474–483. [[CrossRef](#)]
143. Zhang, B.; Feng, Y.; Xie, J.; Lai, D.; Yu, T.; Huang, D. Rubberized geopolymer concrete: Dependence of mechanical properties and freeze-thaw resistance on replacement ratio of crumb rubber. *Constr. Build. Mater.* **2021**, *310*, 125248. [[CrossRef](#)]

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