

Factors affecting durability properties of GPC: A review

Nabaz Yassen Ezuldin^{1,2,a}, Saad Mahmood Raof^{2,b}, Alyaa Abbas Alattar^{1,c}, Hussein Hamada^{3,d*}

¹Technical Engineering College of Kirkuk, Northern Technical University, Kirkuk, Iraq

²College of Engineering, Tikrit University, Iraq

³Al-Qalam University College, Kirkuk 36001, Iraq

Article Info

Abstract

Article history:

Received 09 Jan 2024

Accepted 05 Apr 2024

Keywords:

Geopolymer concrete;
Activator;
Strength;
Durability;
Sustainable;
Environment

The imperative to find sustainable alternatives to conventional cement, given its energy-intensive production and significant environmental impact, has driven research into alternative binder materials for civil infrastructure. This paper explores Geopolymer concrete (GPC), a polymer-based binder technology, as a promising solution to reduce the environmental footprint associated with traditional cement production. The study meticulously examines various aspects of GPC, focusing on its impact on crucial durability properties for infrastructure applications. This includes an in-depth analysis of GPC properties, elucidating characteristics influencing performance. In addition to fundamental properties, the paper critically evaluates the resistance of geopolymer pastes and concrete to a spectrum of extreme conditions. The discussion spans testing methodologies for both heat- and ambient-cured geopolymers, providing insights into their performance and durability across diverse environmental challenges. This comprehensive review aims to enhance the understanding of GPC technology, offering valuable insights for researchers, engineers, and industry professionals committed to sustainable and resilient infrastructure solutions.

© 2024 MIM Research Group. All rights reserved.

1. Introduction

Geopolymer concrete (GPC) stands as a groundbreaking advancement in concrete technology, emerging as a highly sophisticated alternative to conventional ordinary Portland cement (OPC) concrete [1]. This innovative approach in concrete production replaces traditional Portland cement with pozzolanic materials, specifically designed to address the environmental concerns associated with the widespread use of Portland cement [2]. As the second most utilized material globally after water, Portland cement production significantly contributes to carbon dioxide (CO₂) emissions and entails substantial energy consumption, thereby presenting formidable environmental challenges [3].

In addition to its superior strength and durability, GPC offers a myriad of advantages, establishing itself as a compelling choice for contemporary construction practices [4]. Notably, GPC exhibits exceptional early-age strength and benefits from ambient curing conditions, contributing to accelerated construction timelines [5]. The intricacies of GPC's durability and strength hinge on various factors, including the selection of binders, the alkali-activating solution employed, and the nuances of the curing process [6]. This study aims to provide a comprehensive exploration of the inherent strength and durability

*Corresponding author: enghu76@gmail.com

^aorcid.org/0009-0005-0357-1444; ^borcid.org/0000-0002-6791-8268; ^corcid.org/0000-0003-1942-5458;

^dorcid.org/0000-0001-9911-8639

DOI: <https://dx.doi.org/10.17515/resm2024.145ma0109rv>

Res. Eng. Struct. Mat. Vol. x Iss. x (xxxx) xx-xx

characteristics of GPC, with a focal point on understanding the critical interplay of these variables.

Moreover, the incorporation of industrial by-products, such as fly ash (FA) and ground granulated blast-furnace slag (GGBS), into GPC reveals additional benefits, contributing to both environmental sustainability and resource efficiency. A notable environmental advantage lies in the reduced energy requirements for raw material extraction in GPC production [7]. This paper serves as a detailed examination of various facets of GPC, encompassing mix design techniques, the impact of fiber additions on durability and strength properties, and the overall performance of GPC structures.

Despite numerous studies investigating the effects of different factors on the strength and durability of GPC [8-10], geopolymer mortar [11-13], and both [14], recent literature lacks comprehensive reviews, especially within the last three years, focused on the factors affecting the durability of GPC. Hassan et al. [15] studied the mechanical and microstructure properties of GPC and did not address the fire resistance and water permeability of GPC. Johan et al. [13] focused in their study on the effect of source materials on the properties of geopolymer mortar and also did not study factors effecting the fire resistance and water permeability. Zhang et al. [11] investigated the mechanical properties of geopolymer mortar and did not address the GPC properties. Huseien et al. [16] investigated the geopolymer mortar as repair materials and did not focus on the factors effecting the durability of GPC. Ng et al. [14] investigated only compressive strength and microstructure of geopolymer paste, mortar, and concrete. Amran et al. [17] investigated the mechanical and physical properties of GPC only and did not address the durability properties of GPC. Zhang et al. [18] investigated the engineering and fabrication properties of concrete and GPC, but they did not address the fire resistance and water permeability of GPC, as well as did not address the repolymerization process in detail. Ahmed et al. [19] conducted a comprehensive literature review about the mechanical properties of GPC and its effect on the behavior of GPC beams. This paper aims to fill this gap, serving as a valuable resource for researchers, engineers, and practitioners. It offers a thorough understanding of the nuanced aspects of GPC and the factors influencing its strength and durability. The intent is to encourage further exploration and application of this innovative concrete technology in sustainable and resilient construction practices.

1.1 Background

Geopolymers have emerged as a focal point in contemporary research and development, holding substantial promise as ecologically beneficial and sustainable alternatives to traditional cement-based materials [5]. The impetus behind geopolymer research lies in its potential to significantly alleviate the environmental impact associated with conventional Portland cement production [20]. Noteworthy is the fact that the synthesis of geopolymers typically occurs at lower temperatures, resulting in significant reductions in carbon dioxide emissions and overall environmental considerations [21]. Primarily derived from aluminosilicate source materials, geopolymers capitalize on industrial by-products such as fly ash from coal combustion or slag from metallurgical processes [22]. The versatility of these source materials is a central focus of ongoing research, underscoring the imperative to identify and optimize components suitable for geopolymer synthesis.

GPC, an innovative and environmentally friendly alternative to conventional Portland cement-based concrete, distinguishes itself through exceptional strength, durability, and sustainable characteristics [23]. At its core, GPC relies on geopolymers— inorganic materials with a polymer-like structure, often sourced from industrial by-products like fly ash, slag, or other aluminosilicates. The utilization of these industrial residues not only

enhances the sustainability of the concrete but also aligns with the principles of the circular economy by repurposing waste materials.

1.2 Importance of Study

Geopolymer materials are gaining traction as substitutes for traditional construction components; however, many studies are confined to conditions involving heat curing. The widespread acceptance of geopolymer materials, encompassing both mortar and concrete, could be significantly broadened if they prove to be feasibly and economically viable under ambient curing conditions. This study aims to contribute to the ongoing advancements in geopolymer materials by exploring their potential enhancement through the incorporation of various mineral admixtures. The focus is on improving durability properties such as resistance to elevated temperatures, permeability, acid resistance, and sulfate resistance. Ambient curing, which refers to curing at room temperature without the need for specialized curing conditions like high temperatures or steam curing, is crucial for the practical application of geopolymers in real-world construction settings [24]. Generally, the addition of mineral admixtures such as fly ash, silica fume, or GGBFS can enhance the properties of GPC [25]. These admixtures can contribute to increased strength, reduced permeability, and improved durability of GPC [13]. However, the exact effects depend on the specific materials and mix proportions, highlighting the importance of understanding and optimizing these factors for the desired performance of geopolymers.

The continued development of geopolymer materials is crucial for addressing the practical challenges associated with their application, especially in the context of ambient curing conditions. This research seeks to advance the understanding of how different mineral admixtures can positively impact the durability characteristics of geopolymer materials, thereby expanding their practical utility. Of particular interest are properties such as resistance to elevated temperatures, acid resistance, sulfate resistance, and permeability, which play a pivotal role in determining the overall performance and lifespan of structures constructed with geopolymer materials.

2. Polymer and Polymerization Process

The term "polymer process" encompasses a diverse range of activities related to the production, modification, or processing of polymers—large molecules composed of recurring structural units called monomers [26]. These versatile compounds play pivotal roles in numerous industries, including plastics, textiles, adhesives, and various biological applications [27, 28]. The polymer process spans diverse procedures, ranging from the synthesis of polymers to their transformation into practical and usable items [29]. In the context of geopolymer technology, the polymer process takes on a unique significance. An alkaline medium, typified by substances such as sodium hydroxide or potassium hydroxide, proves ideal for observing the polymerization process. Notably, the inclusion of silicates introduces an additional ionic composition, fostering excellent bonding effects within the resulting polymer structure. The concentration of alkali ions, particularly in higher molar concentrations, can expedite the chain reaction among reactants. However, a delicate balance must be struck, as elevated concentrations may lead to a rapid loss of consistency during mixing, given the accelerated pace of the polymerization reaction [30].

A noteworthy observation is the impact of sodium silicate addition on the sodium hydroxide solution's silicate content. This augmentation influences the gel formation, rendering it more prone to rapid polymerization [31]. Insights into the intricacies of the polymer process are pivotal for understanding and optimizing the synthesis of geopolymers, particularly as they pertain to achieving desired properties in GPC. This section illuminates the complex interplay of alkaline mediums, silicate content, and the

kinetics of polymerization, providing a foundational understanding of the polymer process crucial for advancing geopolymer research and application.

Geopolymers, classified as inorganic polymers, exhibit a chemical composition akin to zeolites, with a distinguishing microstructural feature of amorphousness rather than crystallinity [32]. The polymerization process involves a swift reaction facilitated by activator agents on Si-Al minerals, culminating in the formation of a 3D geopolymer chain and the establishment of Si-O-Al-O bonds [33], as shown in Figure 1. This key concept revolves around the amalgamation of Si/Al-rich materials with activator agents, fostering the development of Si-O-Al-O bonds through the polymerization process. GPC undergoes poly-condensation from Si and Al, along with a high alkali content, contributing to strength development [34].

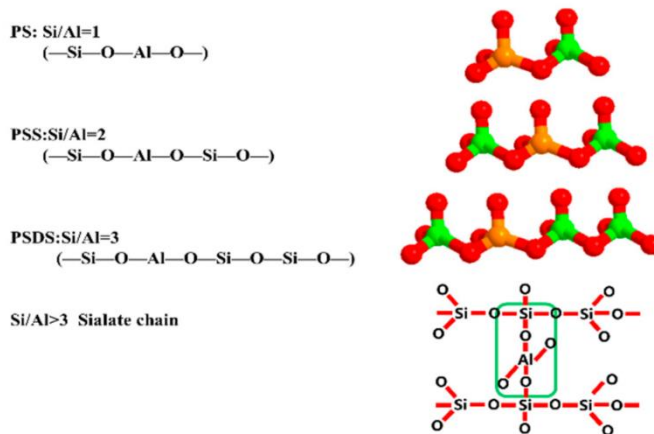


Fig. 1. Model of Geopolymer with various Si/Al molar [33]

Noteworthy is the amorphous nature of GPC, akin to synthetic zeolites, with a chemical composition resembling the zeolitic structure. The geopolymer framework comprises Si-O-Al units, distinct from zeolites, where alternate Si-Al tetrahedra are interconnected in three dimensions by oxygen atoms [35]. The coordination of Al with four oxygen atoms generates a negative disproportion, necessitating cations like Na⁺ and K⁺ to expedite the geopolymerization [36]. Upon the addition of water or additives to NaOH and KOH agents, a reaction ensues, liquefying silica and vigorously reacting with additives to form a geopolymer binder [37]. The incorporation of industrial waste rich in Si and Al enhances the strength of the resulting material [38]. A higher concentration of binder components such as fly ash, GGBS, rice husk ash (RHA), metakaolin (MK), etc., contributes to elevated Si, Al, and CaO content, thereby augmenting strength development. The wide reactivity range of fly ashes influences the evolution of the C-S-H matrix, enhancing tetra-coordination in interlayer spaces.

3. Properties of GPC Mixtures

Concrete, including GPC, which distinguishes itself from conventional Portland cement-based concrete. GPC relies on a unique binder system activated through industrial by-products such as fly ash or slag in combination with alkaline solutions [39]. Table 1 provides an overview of the chemical composition and types of binders employed by various authors in the context of GPC.

Table 1. Chemical compositions of each binder used in the previous studies

Ref	Binder	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	P ₂ O ₅	K ₂ O	Na ₂ O	TiO ₂	L.O.I	SO ₃
	RHA	90	0.46	0.43	1.10	0.77	NA	4.6	NA	NA	3.9	NA
Jindal et al. [40]	Ultra-fine slag (UFS)	33.9	22.6	1.4	32.8	7.8	NA	NA	NA	NA	NA	0.23
Albegm pri et al., [41]	Fly ash	38.4	22.2	12.14	0.88	1.81	NA	NA	2.76	NA	3.1	0.4
	GGBS	50.82	10.19	0.76	26.72	1.89	NA	NA	0.24	NA	1.9	1.02
Mahdikhani and Sarvandi [42]	GGBS	39.61	9.57	1.45	31.68	6.49	0.02	1.97	0.51	0.95	NA	2.5
Petrus et al., [43]	Fly ash	37.6	12.5	20.8	20.7	NA	1.9	2.0	NA	1.3	NA	2.1
Kugler et al., [44]	Fly ash	52.35	25.19	6.22	4.17	1.88	NA	2.09	1.09	1.15	NA	NA
	Concrete rubble	59.5	3.12	1.33	17.85	1.42	NA	1.18	0.20	0.11	NA	NA
Ahmed et al., [45]	ferrosilicon slag	77.7	3.45	11.50	1.96	0.14	NA	0.35	0.26	0.11	3.85	0.39
	alumina waste	2.62	64.5	0.46	0.47	0.13	NA	3.61	4.29	0.13	2.74	0.42
Pham et al., [46]	Fly ash	58.7	22.87	7.31	0.98	0.85	NA	3.6	0.33	1.35	3.53	NA
Hamzah et al., [47]	GGBFS	35.02	13.56	1.41	38.6	8.18	NA	0.80	0.31	0.23	1.89	NA
	Fly ash	57.2	28.8	3.7	5.2	1.6	NA	0.9	0.1	NA	0.22	0.1

As shown in Table 1, silica and alumina oxides constitute the highest percentages among other components in the chemical composition of aluminosilicate materials. These proportion significantly contributes to enhancing the durability of GPC by improving the hardness and density of GPC.

4. Effect of Curing on The Durability of Geopolymer Concrete

GPC undergoes a dynamic evolution of characteristics and behaviors, a transformation intricately linked to the specifics of its curing conditions [48]. Rigorous investigations, involving variations in both curing temperatures and durations, have been instrumental in unraveling the nuanced development of GPC [49]. Diverse studies have probed the behavior of GPC under different curing regimens, exemplified by the work of Chouksey et al. [50], who explored the impact of curing conditions on mechanical and physical properties. Their investigation, employing both oven-curing and ambient curing, revealed higher compressive, flexural, and tensile strengths in oven-cured samples compared to ambient-cured ones. Notably, dry shrinkage and density exhibited an inverse trend, with higher values for ambient-cured samples. Similarly, Poloju and Srinivasu [51], demonstrated the advantages of incorporating fly ash and GGBS with an alkaline activator

(sodium silicate and sodium hydroxide) in GPC, comparing the outcomes of oven curing at 60°C for 24 hours and ambient curing. Their findings underscored the superior strength recorded in oven-cured samples relative to ambient-cured counterparts. Table 2 shows the effect of curing conditions on the GPC.

Table 2. Effect of different curing conditions on the durability and strength of HPC

References	Curing type	Aluminosilicate	Alkali activator	Effect of curing
Gholampour et al. [52]	Ambient and oven-curing	GGBS and fly ash	NaOH and Na ₂ SiO ₃	GPC samples cured by oven show a somewhat higher strength than that of GPC cured by ambient condition. GPC samples have improved properties
Singh and Sandhu [53]	27 and 90 °C	Fly Ash and Alccofine	NaOH and Na ₂ SiO ₃	at 27 and 90 °C owing to the creation of polymer and hydration products. The addition of waste glass powder in GPC containing GGBS and biomedical waste ash at ambient curing led to an enhancement in the properties of GPC more than that of mixtures without waste glass powder to record a 28 days-compressive strength of 48.6 MPa
Suresh et al. [54]	Ambient curing	GGBS and bio-medical waste ash	NaOH and Na ₂ SiO ₃	The compressive strength and durability of GPC improved in the heat curing condition than the ambient curing condition.
Dişçi and Polat [55]	heat + water cured and heat + ambient 90 C for 72.	Perlite, Nano-CaO, and Nano-Al ₂ O ₃	NaOH and Na ₂ SiO ₃	The samples of GPC oven-cured recorded better performance compared to GPC samples that cured at ambient condition
Poloju and Srinivasu [51]	Ambient curing and Oven curing with 60C	GGBS and fly ash	NaOH and Na ₂ SiO ₃	Addition of waste wood ash as fly ash replacement and waste rubber tires as a fiber at ambient curing enhanced the GPC properties.
Arunkumar et al. [56]	Ambient curing	Fly ash and waste wood ash	NaOH and Na ₂ SiO ₃	

Wang et al. [48]	20, 40, 60, 80 and 100 °C	GGBS and fly ash	NaOH and Na ₂ SiO ₃	The strength and durability of GPC increase as the curing temperature increases from 20 to 80 C. while, the performance of GPC starts to decrease as the curing temperature increases more than 80 °C. Heat curing enhance the durability
Saif et al. [57]	ambient curing and 60 °C heat curing	Fly ash, GGBS, and mtakaolin	NaOH and Na ₂ SiO ₃	properties of GPM containing MK more than ambient curing for all aggressive environments.
Noushini and Castel [58]	Ambient curing and thermal curing 60, 75, and 90 C	fly ash	NaOH and Na ₂ SiO ₃	Thermal curing has a significant influence in improve durability properties of GPC made of low calcium fly ash.

The curing process for GPC unfolds in distinct stages, each contributing to the material's final properties. Initial heat curing involves subjecting specimens to varying temperatures in an oven, a critical step in determining the optimal curing temperature for complete polymerization over 24 hours [59]. Subsequently, a second phase employs steam curing in an accelerated curing tank at diverse temperatures for 18 hours, a method proven to enhance compressive strength significantly [60]. Following these accelerated curing steps, standard water curing is applied, culminating in the final stage of fixing the model at room temperature [61]. An alternative curing method involves microwave household curing at 2.45 GHz, where variations in wattage and duration impact the temperature profile in the center of the samples [62]. Furthermore, researchers have delved into the impact of both microwave and conventional curing methods on the compressive strength of geopolymer mortar. The investigation incorporated standard heat curing parameters at 65 °C, coupled with a 5-minute curing duration using a 90-W microwave. In parallel, diverse studies scrutinized alternative curing conditions, encompassing lime-water curing (LWC), sealed ambient curing, and heat curing, spanning both GPC and ordinary Portland cement concrete (OPCC) [63].

The alkaline activator in GPC mainly involves of a combination of sodium silicate (Na₂SiO₃) and sodium hydroxide (NaOH) [64]. The chemical composition can be represented as: Sodium Hydroxide (NaOH) and Sodium Silicate (Na₂SiO₃), and to calculate the Molar Ratios, should be applied the following calculations:

- Sodium Oxide (Na₂O) molar mass = 62 g/mol
- Silicon Dioxide (SiO₂) molar mass = 60.09 g/mol

As reported by Cheng et al. [65], the molar ratio of Na₂O to SiO₂ in sodium silicate (Na₂SiO₃) is ranging between 1.38 and 1.93, and this proportion might be changed according to the mix design and specification required. This means that for every mole of Na₂O in the

sodium silicate, there are 1.38 moles of SiO_2 . The molar ratios of Na_2O to SiO_2 in the alkaline activator can importantly affect the durability of GPC.

5. Durability of GPC

The durability of GPC consistently surpasses that of conventional Portland cement concrete, owing to its distinctive material composition and manufacturing method [66]. GPC exhibits exceptional resistance to acids and sulfates, attributed to the absence of gaps between binding materials, ensuring heightened durability [67]. This advantage extends to the preservation of the reinforcing steel's integrity within the concrete for extended periods, resulting in significantly less volume loss compared to normal concrete. Key durability properties of GPC encompass resistance to acid attacks, resistance to sulfate attacks, fire resistance, and permeability.

5.1. Resistance to Acid Attack

In a study comparing GPC (composed of fly ash and slag) with O.P.C. concrete in structural applications, slag demonstrated superior acid resistance when exposed to sulfuric acid [13]. A comprehensive durability examination involving exposure to seawater (5% NaCl), sulfate attack (5% sodium sulfate or 5% magnesium sulfate), and acid attack (5% sulfuric acid) confirmed the exceptional durability of GPC over normal concrete. Acid attack proved to be the most challenging for both geopolymer and standard concrete, with GPC consistently outperforming ordinary Portland cement specimens in all durability tests [68]. In a study by Valencia-Saavedra et al. [69], the exposure of normal concrete samples to H_2SO_4 for 7, 28, 90, 180, and 360 days significantly affected the surface of the samples. Clear deterioration in the control concrete was observed after 28 days of exposure to H_2SO_4 , intensifying over prolonged exposure periods. In contrast, the effect of the acid solution on GPC was notably lower compared to normal concrete, as illustrated in Figure 2. While, table 3 shows the resistance of geopolymer against acid attacks.

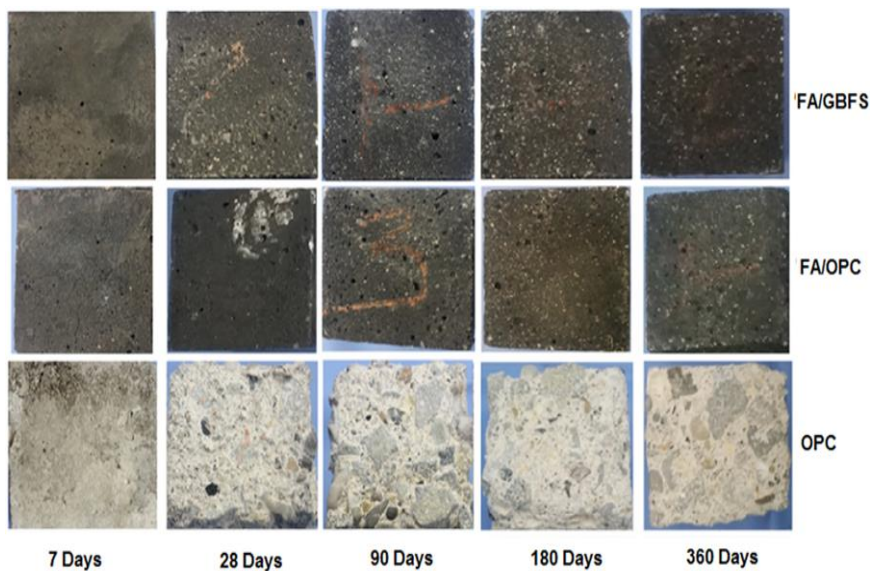


Fig. 2. Appearance of concrete samples exposed to H_2SO_4 for different periods [69]

Table 3. Resistance of geopolymer against acid attacks

References	Type of acid	Aluminosilicate	Alkali activator	Effect on the GPC
Albegmprli et al., [41]	H ₂ SO ₄ % in 0, 5, and 10%	GGBS, fly ash, and cement	NaOH and Na ₂ SiO ₃	Even though the GPC has better resistance to acid attacks than cement concrete. However, degradation in the properties of GPC has been shown also due to exposure to the H ₂ SO ₄ , especially at a concentration of 10%. The GPC samples exposed to the acid solutions had lower mass loss of up to 6%, while in the case of normal concrete reached up to 19%. Minor deterioration was noted for samples of GPC exposed to H ₂ SO ₄ in terms of mass loss, neutralization depth, and visual appearance.
Valencia-Saavedra et al., [69]	Acetic acid (CH ₃ -COOH) and sulfuric acid (H ₂ SO ₄)	Fly ash, GGBS, and cement	NaOH and Na ₂ SiO ₃	GPC with crumb rubber showed poorer resistance to acid attacks (H ₂ SO ₄ and HCl).
Yang et al. [70]	H ₂ SO ₄	Metakaolin and fly ash	NaOH and Na ₂ SiO ₃	
Pham et al. [71]	H ₂ SO ₄	Ultrafine slag, cement, and fly ash	NaOH and Na ₂ SiO ₃	

5.2. Resistance to Sulfate Attacks

GPC is recognized for its potential durability advantages over traditional Portland cement concrete [72], particularly in terms of superior resistance to various chemical attacks, including sulfate attacks [73]. Sulfate attack is a concrete deterioration process initiated by the reaction of sulfates in the environment with concrete components, leading to the formation of expansive and disruptive compounds [74]. Unlike conventional Portland cement concrete, GPC employs industrial by-products like fly ash or slag as binders, contributing to an inherently improved resistance to sulfate attack [75].

The geopolymerization process involved in GPC results in the formation of a robust three-dimensional network structure, imparting greater resilience to chemical attacks when compared to the calcium silicate hydrate gel found in traditional concrete [76]. The resistance of GPC to sulfate attack is further influenced by factors such as specific mix design, curing conditions, and the type and concentration of sulfates in the environment [68, 75]. Numerous research studies have been conducted to evaluate the durability properties of GPC, with a specific focus on its resistance to sulfate attack. The insights

gained from these studies contribute to an evolving understanding of the material's performance. Table 4 provides a summary of results obtained from previous studies related to the resistance of GPC to sulfate attacks.

Table 4. Resistance of geopolymer against sulfate attacks

References	Aluminosilicate	Alkali activator	Effect on the GPC
Uğurlu et al. [77]	GGBS	Na_2SiO_3 and NaOH	The resistance to sulfate attacks increases as the binder content amount in the GPC mix increases.
Guo et al. [78]	Metakaolin (MK)	Na_2SiO_3 and NaOH	The resistance against sulfate attacks improved due to the incorporation of hybrid fibers to reduce the stress, preventing the formation of pore cracks and prevent the development of micro-cracks.
Guo et al. [79]	Fly ash and steel slag	Na_2SiO_3 and NaOH	The addition of steel fiber into GPC mix enhanced the strength. Also, the steel fiber has a significant role in the resistance of GPC mortar against sulfate attacks.
Kuri et al. [80]	Slag and fly ash	Na_2SiO_3 and NaOH	The low content of calcium in slag assists in improving the resistance of the GPC samples against sulfate attacks.

Sulfate ions exist in water and soil in various forms [81]. These ions can penetrate concrete samples through the pores on the concrete surface, subsequently reacting with cement hydration to produce gypsum and ettringite. This reaction can lead to spalling and cracks in the concrete surfaces [82]. Lingyu et al. [83] observed that the permeability of GPC samples increases with an elevated Si/Al ratio in GPC made of metakaolin. Additionally, Nasir et al. [84] reported that exposure of GPC samples to sodium sulfate (Na_2SO_4) results in a reduction in the Ca/Si ratio. The nature of GPC samples makes them more durable and has higher resistance against sulfate attacks as compared to normal concrete [75].

5.3. Permeability of Geopolymer

Geopolymers, like other materials, demonstrate diverse permeability characteristics influenced by factors such as composition, curing conditions, and microstructure [85]. Inorganic geopolymers typically arise from the combination of aluminosilicate substances with an alkaline activator solution, known for their robust construction and chemical resistance [22]. Permeability, defined as the material's ability to allow the passage of gases, liquids, or ionic species, including water, is a critical attribute in assessing durability properties [86]. The presence of pores in concrete renders it vulnerable to the ingress of detrimental ions, leading to various adverse effects. Water, in particular, can induce ice

formation in large paste pores, facilitate leaching of compounds from the paste, transport chlorides or acids into the paste, and result in the leaching of calcium hydroxide from the cement paste. Table 5 presents the factors affecting the permeability of GPC.

Table 5. Resistance of geopolymer against permeability

References	Alimosilicate	Alkali activator	Effect on the GPC
Ross et al. [87]	Fly ash	Na_2SiO_3 and NaOH	The geopolymer paste has lower permeability compared to the cement paste, its recorded only $0.26 \pm 0.09 \mu\text{D}$ at 28 curing days. The permeability of GPC decreases due to increase of confining
Nasvi et al. [88]	Fly ash	Na_2SiO_3 and NaOH	Pressure and decrease the connectivity of pores. The coefficient of water permeability for the GPC made of biomass aggregate was not considerably different from that of normal concrete prepared from normal aggregates. However, the use of agricultural waste improves waste management and encourages the adoption of eco-friendly concrete. The permeability
Arafa et al. [89]	Fly ash	Na_2SiO_3 and NaOH	significant affected by the pore connectivity, pore size, and porosity of the GP foam concrete.
Zhang et al. [90]	MK and fly ash	Na_2SiO_3 and NaOH	

5.4. Fire Resistance

GPC, as a material, generally exhibits fire-resistant properties [91]. However, the dehydration and breakdown of crystalline hydrates, aggregate types, permeability, and other factors result in a residual strength of ordinary Portland cement (OPC) concrete typically not exceeding 20-30% after exposure to temperatures between 800°C and 1000°C [92]. The temperature range of 25-910°C induces structural changes in the cement gels of concrete PENLY and TEMELIN under heat load [93]. Alterations in micro- and mesoporous areas are studied through physical nitrogen adsorption and mercury porosimeter. Up to around 500°C, corresponding to the disintegration of $\text{Ca}(\text{OH})_2$ into CaO, there is an observed increase in pore volume and surface area.

Investigating geopolymers and geopolymer-aggregate composites derived from class F fly ash, samples heated to 800°C showed strength improvements of about 53% for geopolymers [94]. However, geopolymer/aggregate composites, using the same geopolymer binder compositions, experienced a strength decrease of up to 65%. Dilatometry measurements revealed linear growth in aggregate size with increasing temperature, expanding by approximately 1.5% to 2.5% at 800 °C. Conversely, the geopolymer matrix shrank by about 1% between 200 and 300 °C and an additional 0.6%

between 700°C and 800°C [94]. Table 6 shows the resistance of GPC against the fire resistance.

Table 6. Resistance of geopolymer against sulfate attacks

References	Aluminosilicate	Alkali activator	Effect on the GPC
Wang et al. [95]	MK and fly ash	NaOH and Na ₂ SO ₄	The addition of kaliophilite significantly enhanced the resistance against fire of GPC samples.
Nuaklong et al. [96]	Fly ash	NaOH and Na ₂ SO ₄	The addition of granite waste into the oven-dried and air-dried aggregates of the GPC mixture has a minor effect on the fire resistance of GPC
Abd Razak et al. [97]	Fly ash	NaOH and Na ₂ SO ₄	Increase the temperature from 500 C to 1200 C led to reduce the performance of GPC sample. However, the GPC samples still better strength and durable than cement concrete.
Nuaklong et al. [98]	Fly ash, rice husk ash, and nano-silica	NaOH and Na ₂ SO ₄	

As indicated in Table 6, several factors influence the fire resistance of GPC. Nuaklong et al. [98], conducted a study on the impact of high calcium fly ash (HCFA), nano silica (nS), and rice husk ash (RHA) as binder materials in the production of GPC containing recycled aggregate concrete (RAC). They observed that the use of recycled aggregate (RCA) in GPC led to an enhancement in the loss of strength and durability during the initial 30 minutes of exposure to fire. However, GPC samples made of both RCA and natural aggregate no longer maintained their dimensional stability, as depicted in Figure 3.

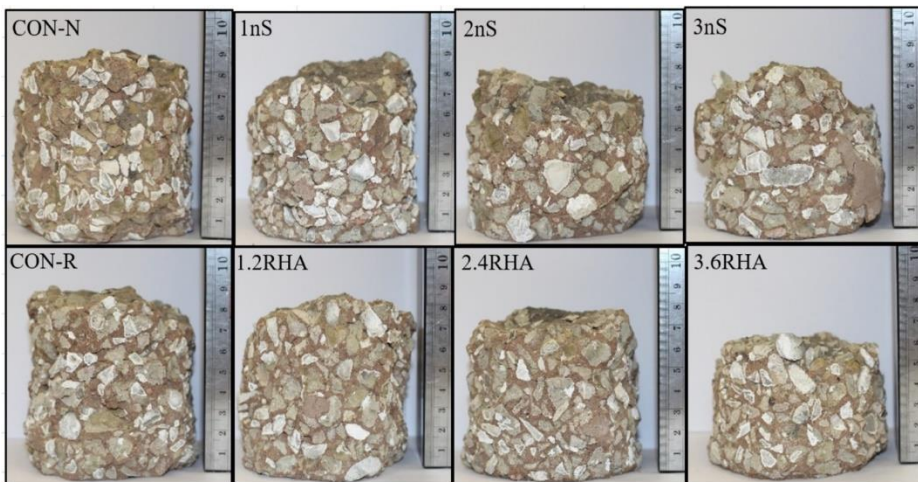


Fig. 3. Shape of fire-damaged samples exposed to fire for 90 minutes [98]

5.5 Chloride Ion Penetration

Chloride ion penetration is one of the important tests that determine the durability of GPC, and existence in marine and coastal areas. Chloride ions can penetrate the concrete matrix and reach the embedded steel reinforcement, leading to corrosion and ultimately compromising the structural integrity of the GPC. Factors influencing chloride ion penetration include the permeability and porosity of the concrete, the existence of cracks or other defects, the curing regime, and the type and content of SCMs. Saif et al. [57] examined the effect of curing conditions and MK content on the resistance against chloride penetration. They exposed the GPC samples to chemical solutions of (10% NaCl, H₂SO₄ (pH=3, and 10% MgSO₄) for 10 weeks then tested the compressive strength and change in weight. They observed that the use of MK in GPM displays better performance than that of normal concrete when exposed to harsh environments. Another study by Okoye et al. [99] examined the effect of silica fume on the durability of GPC by immersing the samples in 5% sodium chloride (NaCl) and 2% sulfuric acid (H₂SO₄) solutions. They measured the weight loss and compressive strength loss after exposure the samples for different periods. One of the samples was fixed as control mix made from OPC concrete for comparison, called M40. They observed that there was a minor losing in weight for the GPC samples due to exposure these samples to NaCl solution in different periods. However, the GPC samples have lower weight losses than that of M40 as shown in Figure 4, means that GPC samples have higher resistant against chloride attack.

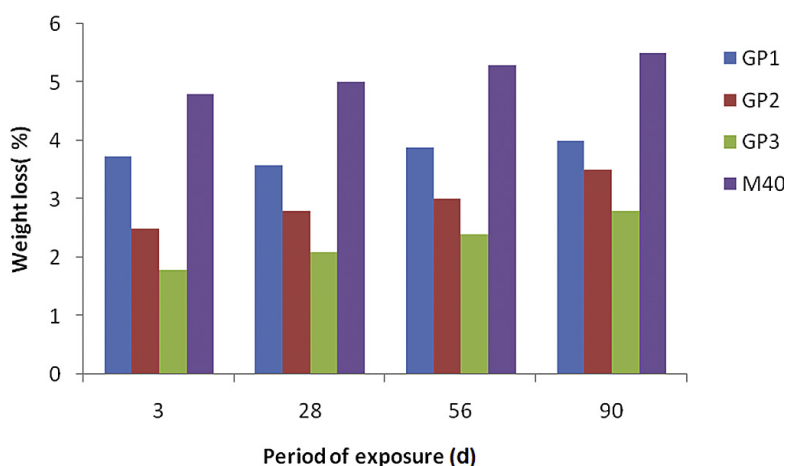


Fig. 4. Weight loss vs exposure periods for GPC and M40 samples in 5% NaCl [99]

Chindaprasirt and Chalee [100] investigated the influence of the concentration of sodium hydroxide on steel corrosion and chloride penetration of GPC containing fly ash at marine environment. They used different concentrations of sodium hydroxide from 8 to 18 molarity. The samples of GPC were tested for corrosion, chloride penetration, and compressive strength after three years exposure. They found that the increase concentration of sodium hydroxide led to reduce the corrosion and chloride penetration values. Therefore, it has a positive effect on the durability of GPC. Halim and Ekaputri [101] examined the effect of salt water on the performance of GPC made of sodium silicate and 8 molar sodium hydroxides as the alkali solution and fly ash as binder material. They immersed some samples in 3.5% concentration of salt water, while other samples were cured in normal water, as a control samples. They observed that the chloride penetration in GPC is higher than normal cement concretes, and GPC samples have higher compressive strength than that of normal cement concretes.

5.6 Dry Shrinkage

Dry shrinkage is one of the factors effecting the durability of GPC. It refers to the reduction in volume that occurs when moisture is lost from the concrete without the presence of any external factors such as loading or temperature changes. Dry shrinkage in GPC is primarily attributed to the evaporation of water from the pore structure, leading to a decrease in interparticle forces and subsequent shrinkage. Factors affecting dry shrinkage include the curing conditions, composition of the geopolymer binder, admixtures, and aggregate properties. Numerous researchers investigated the factors effecting dry shrinkage of GPC. For instance, Ahmed et al. [102] examined the effect of clay brick waste on the dry shrinkage of GPC made of metakaolin as a binder material. They used two groups of clay brick waste, it was clay brick powder as partial metakaolin replacement in proportions of 10, 15 and 20% by weight, the other group involved of waste clay brick as a partial aggregate replacement in proportions of 10, 20 and 30% by volume. They observed that the drying shrinkage of GPC samples increased at early age, and then decreased after 28 days due to use of clay brick waste as powder in GPC, as shown in Figure 5.

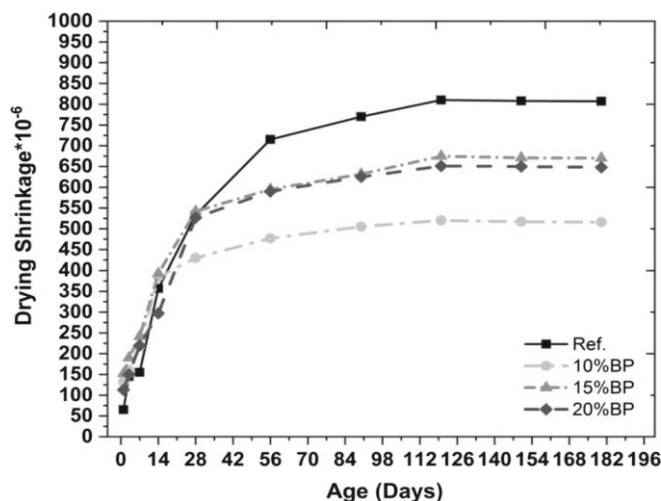


Fig. 5 Effect of clay brick waste powder (BP) on the drying shrinkage of GPC [102]

As mentioned before, drying shrinkage of GPC can be affected by different factors related to curing duration, materials sources and characteristics, mix design, and others. Ridditirud et al. [103] conducted a study on the factors affecting the drying shrinkage of GPC made of fly ash. They investigate effect of NaOH concentration, curing temperature, liquid-to-ash ratio, and NaOH concentration on the drying shrinkage of GPC. The results obtained from their study indicated to that the drying shrinkage of GPC is mostly influenced by liquid-to-ash ratio and curing temperature. The increase in liquid-to-ash ratio from 0.4 to 0.7 led to significant increase the drying shrinkage of GPC. Neupane et al. [104] investigated the influence of two types of powders on the drying shrinkage of GPC, namely fly ash and cement at ambient curing condition. They observed that the drying shrinkage of cement concrete was similar to that of GPC. This value also depends on numerous factors such as additives types, workability, water content, and binder types.

5.7 Carbonation

Carbonation is an important durability concern for GPC structures, as it can lead to a reduction in alkalinity and subsequent corrosion of embedded steel reinforcement. Carbonation occurs when carbon dioxide from the atmosphere reacts with calcium

hydroxide in the concrete to form calcium carbonate. This process reduces the pH of the concrete, which can accelerate the corrosion of steel reinforcement. Factors affecting carbonation include the content and type of alkaline activator, exposure to carbon dioxide, curing conditions, and the existence of SCMs. Grengg et al. [105] observed that the corrosion rates of GPC was ranging between (1.4 mm/a) and (13.3 mm/a), and reported that the well-designed GPC mixtures significantly contribute in enhancing resistance against carbonation. As reported by Law et al. [106], the carbonation is hypothesized as the reaction of the CO₂ with sodium hydroxide (NaOH) making sodium carbonate NaCO₃ + H. The lower content of 7.5% in geopolymer mortar having a somewhat lesser pH than those having content 15%. Zhuguo and Sha [107] investigated the effect of two waste materials, namely GGBS and fly ash on the carbonation resistance of geopolymer mortars and GPC at various elapsed times. They found that the resistance against carbonation of GGBS and fly ash-based GPC treated at ambient curing is lower than those of normal cement concretes. Finally, they concluded that the increase of NaOH, GGBS ratios, and GGBS fineness, leads to increase of carbonation resistance of GPC and GP mortars. For long curing age, Pasupathy et al. [108] examined the carbonation resistance of GPC exposed to normal conditions for eight years. They detected that the carbonation degree of GPC is extremely affected by the activator materials of GPC. The first group of GPC samples including Na₂SiO₃ activator, 25% GGBFS and 75% fly ash presented a weak resistance against carbonation compared to normal cement concretes. But, the second group of GPC samples involved 30% GGBS and 70% fly ash and without additional Na₂SiO₃ activator, was alike to cement concrete samples.

6. Conclusion

In conclusion, this paper underscores the remarkable potential of geopolymers as a cutting-edge and environmentally friendly class of materials, demonstrating numerous advantages over traditional Portland cement. The findings from this study shed light on the effect of various factors on the durability properties of GPC, emphasizing the following key points:

- Geopolymers significantly reduce the carbon footprint associated with construction materials by utilizing industrial by-products and scraps, thereby contributing to sustainable and eco-friendly practices in the construction industry.
- Geopolymers exhibit exceptional mechanical properties, including impressive compressive strength and durability. These attributes position geopolymers as promising alternatives to traditional building materials, enhancing overall structural integrity.
- The inherent resistance of geopolymers to a diverse range of chemical agents makes them invaluable in applications within the chemical industry and for waste encapsulation, broadening their utility across various sectors.
- Properly formulated and cured geopolymers can exhibit low permeability, proving advantageous in situations where resistance to water and gas penetration is crucial for the longevity of structures.
- Geopolymers showcase better resistance against acid and sulfate attacks as compared to normal concrete.
- Geopolymers showcase inherent fire-resistant characteristics, making them highly desirable for applications in fire-prone environments and the development of fireproof building materials.
- The GPC samples have better resistance against chloride and carbonation than that of normal cement concrete. Besides, numerous factors affect the carbonation and chloride penetration such as the permeability and porosity of the concrete, the existence of cracks, the curing regime, the SCM type, etc.

In light of their demonstrated durability, strength, and resilience to extreme climatic conditions, geopolymers emerge as a viable and sustainable alternative to conventional construction and building materials. As technology and knowledge progress, the increased integration of geopolymers holds the promise of fostering sustainable practices in building, infrastructure, and various industrial applications. The comprehensive exploration of durability properties, including resistance to acid and sulfate attacks, permeability, and fire resistance, contributes valuable insights for researchers, engineers, and practitioners engaged in the pursuit of resilient and environmentally friendly construction solutions.

References

- [1] Danish A, Ozbakkaloglu T, Mosaberpanah MA, Salim MU, Bayram M, Yeon JH, et al. Sustainability benefits and commercialization challenges and strategies of geopolymer concrete: A review. *Journal of Building Engineering*. 2022;105005. <https://doi.org/10.1016/j.jobe.2022.105005>
- [2] Shehata N, Mohamed O, Sayed ET, Abdelkareem MA, Olabi A. Geopolymer concrete as green building materials: Recent applications, sustainable development and circular economy potentials. *Science of the Total Environment*. 2022;836:155577. <https://doi.org/10.1016/j.scitotenv.2022.155577>
- [3] Adesina A. Recent advances in the concrete industry to reduce its carbon dioxide emissions. *Environmental Challenges*. 2020;1:100004. <https://doi.org/10.1016/j.envc.2020.100004>
- [4] Pradhan P, Dwibedy S, Pradhan M, Panda S, Panigrahi SK. Durability characteristics of geopolymer concrete-Progress and perspectives. *Journal of Building Engineering*. 2022;105100. <https://doi.org/10.1016/j.jobe.2022.105100>
- [5] Sbahieh S, McKay G, Al-Ghamdi SG. Comprehensive Analysis of Geopolymer Materials: Properties, Environmental Impacts, and Applications. *Materials*. 2023;16(23):7363. <https://doi.org/10.3390/ma16237363>
- [6] Qaidi S, Najm HM, Abed SM, Ahmed HU, Al Dughaiishi H, Al Lawati J, et al. Fly ash-based geopolymer composites: A review of the compressive strength and microstructure analysis. *Materials*. 2022;15(20):7098. <https://doi.org/10.3390/ma15207098>
- [7] Manzoor T, Bhat JA, Shah AH. Advancements in Geopolymer Concrete: A State-of-the-Art Analysis of Its Mechanical and Durability Features. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*. 2023:1-40. <https://doi.org/10.1007/s40996-023-01261-0>
- [8] Amran YHM, Alyousef R, Alabduljabbar H, El-Zeadani M. Clean production and properties of geopolymer concrete; A review. *Journal of Cleaner Production*. 2020;251:119679. <https://doi.org/10.1016/j.jclepro.2019.119679>
- [9] Zhang P, Wang K, Li Q, Wang J, Ling Y. Fabrication and engineering properties of concretes based on geopolymers/alkali-activated binders - A review. *Journal of Cleaner Production*. 2020;258:120896. <https://doi.org/10.1016/j.jclepro.2020.120896>
- [10] Hassan A, Arif M, Shariq M. Use of geopolymer concrete for a cleaner and sustainable environment "A review of mechanical properties and microstructure. *Journal of Cleaner Production*. 2019;223:704-28. <https://doi.org/10.1016/j.jclepro.2019.03.051>
- [11] Zhang P, Zheng Y, Wang K, Zhang J. A review on properties of fresh and hardened geopolymer mortar. *Composites Part B: Engineering*. 2018;152:79-95. <https://doi.org/10.1016/j.compositesb.2018.06.031>
- [12] Fahim Huseien G, Mirza J, Ismail M, Ghoshal SK, Abdulameer Hussein A. Geopolymer mortars as sustainable repair material: A comprehensive review. *Renewable and Sustainable Energy Reviews*. 2017;80:54-74. <https://doi.org/10.1016/j.rser.2017.05.076>
- [13] John SK, Nadir Y, Girija K. Effect of source materials, additives on the mechanical properties and durability of fly ash and fly ash-slag geopolymer mortar: A review.

- Construction and Building Materials. 2021;280:122443. <https://doi.org/10.1016/j.conbuildmat.2021.122443>
- [14] Ng C, Alengaram UJ, Wong LS, Mo KH, Jumaat MZ, Ramesh S. A review on microstructural study and compressive strength of geopolymer mortar, paste and concrete. Construction and Building Materials. 2018;186:550-76. <https://doi.org/10.1016/j.conbuildmat.2018.07.075>
- [15] Hassan A, Arif M, Shariq M. Use of geopolymer concrete for a cleaner and sustainable environmentâ€"A review of mechanical properties and microstructure. Journal of cleaner production. 2019;223:704-28. <https://doi.org/10.1016/j.jclepro.2019.03.051>
- [16] Huseien GF, Mirza J, Ismail M, Ghoshal S, Hussein AA. Geopolymer mortars as sustainable repair material: A comprehensive review. Renewable and Sustainable Energy Reviews. 2017;80:54-74. <https://doi.org/10.1016/j.rser.2017.05.076>
- [17] Amran YM, Alyousef R, Alabduljabbar H, El-Zeadani M. Clean production and properties of geopolymer concrete; A review. Journal of Cleaner Production. 2020;251:119679. <https://doi.org/10.1016/j.jclepro.2019.119679>
- [18] Zhang P, Wang K, Li Q, Wang J, Ling Y. Fabrication and engineering properties of concretes based on geopolymers/alkali-activated binders-A review. Journal of Cleaner Production. 2020;258:120896. <https://doi.org/10.1016/j.jclepro.2020.120896>
- [19] Ahmed HU, Mahmood LJ, Muhammad MA, Faraj RH, Qaidi SM, Sor NH, et al. Geopolymer concrete as a cleaner construction material: An overview on materials and structural performances. Cleaner Materials. 2022;5:100111. <https://doi.org/10.1016/j.clema.2022.100111>
- [20] Mortada Y, Masad E, Kogbara RB, Mansoor B, Seers T, Hammoud A, et al. Development of Ca (OH) 2-based Geopolymer for Additive Manufacturing Using Construction Wastes and Nanomaterials. Case Studies in Construction Materials. 2023:e02258. <https://doi.org/10.1016/j.cscm.2023.e02258>
- [21] Freire AL, JosÃ© HJ, Moreira RdFPM. Potential applications for geopolymers in carbon capture and storage. International Journal of Greenhouse Gas Control. 2022;118:103687. <https://doi.org/10.1016/j.ijggc.2022.103687>
- [22] Luhar I, Luhar S. A comprehensive review on fly ash-based geopolymer. Journal of Composites Science. 2022;6(8):219. <https://doi.org/10.3390/jcs6080219>
- [23] Abdellatif M, Abd Elrahman M, Abadel AA, Wasim M, Tahwia A. Ultra-high performance concrete versus ultra-high performance geopolymer concrete: Mechanical performance, microstructure, and ecological assessment. Journal of Building Engineering. 2023;79:107835. <https://doi.org/10.1016/j.jobe.2023.107835>
- [24] Zhang H, Li L, Yuan C, Wang Q, Sarker PK, Shi X. Deterioration of ambient-cured and heat-cured fly ash geopolymer concrete by high temperature exposure and prediction of its residual compressive strength. Construction and Building Materials. 2020;262:120924. <https://doi.org/10.1016/j.conbuildmat.2020.120924>
- [25] Singh RP, Vanapalli KR, Cheela VRS, Peddireddy SR, Sharma HB, Mohanty B. Fly ash, GGBS, and silica fume based geopolymer concrete with recycled aggregates: Properties and environmental impacts. Construction and Building Materials. 2023;378:131168. <https://doi.org/10.1016/j.conbuildmat.2023.131168>
- [26] Hossain KR, Jiang P, Yao X, Wu J, Hu D, Yang X, et al. Additive Manufacturing of Polymer-Based Lubrication. Macromolecular Materials and Engineering. 2023;308(11):2300147. <https://doi.org/10.1002/mame.202300147>
- [27] Mukherjee C, Varghese D, Krishna J, Boominathan T, Rakeshkumar R, Dineshkumar S, et al. Recent Advances in Biodegradable Polymersâ€"Properties, Applications and Future Prospects. European Polymer Journal. 2023;112068. <https://doi.org/10.1016/j.eurpolymj.2023.112068>
- [28] El-Ghoul Y, Alminderej FM, Alsubaie FM, Alrasheed R, Almousa NH. Recent Advances in Functional Polymer Materials for Energy, Water, and Biomedical Applications: A Review. Polymers. 2021;13(24):4327. <https://doi.org/10.3390/polym13244327>

- [29] El Itawi H, Fadlallah S, Allais F, Perre P. Green assessment of polymer microparticles production processes: a critical review. *Green Chemistry*. 2022;24(11):4237-69. <https://doi.org/10.1039/D2GC00578F>
- [30] Mao J, Li C, Jiang H, Zhang H, Yang X, Lin C, et al. Preparation of a novel polymer suspensions with high stabilization, and their superior performances in high salinity. *Journal of Molecular Structure*. 2024;1297:136922. <https://doi.org/10.1016/j.molstruc.2023.136922>
- [31] Dai X, Aydin S, Yardimci MY, De Schutter G. Rheology and structural build-up of sodium silicate-and sodium hydroxide-activated GGBFS mixtures. *Cement and Concrete Composites*. 2022;131:104570. <https://doi.org/10.1016/j.cemconcomp.2022.104570>
- [32] Ozen S, Uzal B. Effect of characteristics of natural zeolites on their geopolymerization. *Case Studies in Construction Materials*. 2021;15:e00715. <https://doi.org/10.1016/j.cscm.2021.e00715>
- [33] Wang H, Wu H, Xing Z, Wang R, Dai S. The effect of various Si/Al, Na/Al molar ratios and free water on micromorphology and macro-strength of metakaolin-based geopolymer. *Materials*. 2021;14(14):3845. <https://doi.org/10.3390/ma14143845>
- [34] Ahmed HU, Mohammed AA, Rafiq S, Mohammed AS, Mosavi A, Sor NH, et al. Compressive strength of sustainable geopolymer concrete composites: a state-of-the-art review. *Sustainability*. 2021;13(24):13502. <https://doi.org/10.3390/su132413502>
- [35] Elgarahy AM, Maged A, Eloffy M, Zahran M, Kharbish S, Elwakeel KZ, et al. Geopolymers as sustainable eco-friendly materials: Classification, synthesis routes, and applications in wastewater treatment. *Separation and Purification Technology*. 2023:124631. <https://doi.org/10.1016/j.seppur.2023.124631>
- [36] Shilar FA, Ganachari SV, Patil VB, Khan TY, Khadar SDA. Molarity activity effect on mechanical and microstructure properties of geopolymer concrete: A review. *Case Studies in Construction Materials*. 2022;16:e01014. <https://doi.org/10.1016/j.cscm.2022.e01014>
- [37] Farooq F, Jin X, Javed MF, Akbar A, Shah MI, Aslam F, et al. Geopolymer concrete as sustainable material: A state of the art review. *Construction and Building Materials*. 2021;306:124762. <https://doi.org/10.1016/j.conbuildmat.2021.124762>
- [38] Liu J, Doh J-H, Dinh HL, Ong DE, Zi G, You I. Effect of Si/Al molar ratio on the strength behavior of geopolymer derived from various industrial waste: A current state of the art review. *Construction and Building Materials*. 2022;329:127134. <https://doi.org/10.1016/j.conbuildmat.2022.127134>
- [39] de Oliveira LB, de Azevedo AR, Marvila MT, Pereira EC, Fediuk R, Vieira CMF. Durability of geopolymers with industrial waste. *Case Studies in Construction Materials*. 2022;16:e00839. <https://doi.org/10.1016/j.cscm.2021.e00839>
- [40] Jindal BB, Jangra P, Garg A. Effects of ultra fine slag as mineral admixture on the compressive strength, water absorption and permeability of rice husk ash based geopolymer concrete. *Materials Today: Proceedings*. 2020;32:871-7. <https://doi.org/10.1016/j.matpr.2020.04.219>
- [41] Albegmprli HM, Al-Qazzaz ZK, Rejeb SK. Strength performance of alkali activated structural lightweight geopolymer concrete exposed to acid. *Ceramics International*. 2022;48(5):6867-73. <https://doi.org/10.1016/j.ceramint.2021.11.240>
- [42] Mahdikhani M, Hatamiyan Sarvandani M. Assessment of the bending bearing capacity of the GGBFS-based geopolymer concrete beams exposed to acidic environment. *Archives of Civil and Mechanical Engineering*. 2021;21:1-20. <https://doi.org/10.1007/s43452-021-00223-5>
- [43] Petrus HTBM, Fairuz FI, Sa N, Olvianas M, Astuti W, Jenie SA, et al. Green geopolymer cement with dry activator from geothermal sludge and sodium hydroxide. *Journal of*

- Cleaner Production. 2021;293:126143.
<https://doi.org/10.1016/j.jclepro.2021.126143>
- [44] Kugler F, Karrer J, Krcmar W, Teipel U. Setting behavior and mechanical properties of concrete rubble fly ash geopolymers. *Open Ceramics*. 2022;11:100286.
<https://doi.org/10.1016/j.oceram.2022.100286>
- [45] Ahmed MM, El-Naggar K, Tarek D, Ragab A, Sameh H, Zeyad AM, et al. Fabrication of thermal insulation geopolymer bricks using ferrosilicon slag and alumina waste. *Case Studies in Construction Materials*. 2021;15:e00737.
<https://doi.org/10.1016/j.cscm.2021.e00737>
- [46] Pham DQ, Nguyen TN, Le ST, Pham TT, Ngo TD, editors. The structural behaviours of steel reinforced geopolymer concrete beams: An experimental and numerical investigation. *Structures*; 2021: Elsevier.
<https://doi.org/10.1016/j.istruc.2021.04.077>
- [47] Hamzah HK, Huseien GF, Asaad MA, Georgescu DP, Ghoshal S, Alrshoudi F. Effect of waste glass bottles-derived nanopowder as slag replacement on mortars with alkali activation: Durability characteristics. *Case Studies in Construction Materials*. 2021;15:e00775. <https://doi.org/10.1016/j.cscm.2021.e00775>
- [48] Wang J, Xie J, Wang C, Zhao J, Liu F, Fang C. Study on the optimum initial curing condition for fly ash and GGBS based geopolymer recycled aggregate concrete. *Construction and Building Materials*. 2020;247:118540.
<https://doi.org/10.1016/j.conbuildmat.2020.118540>
- [49] Zia ul Haq M, Sood H, Kumar R, editors. AI-Assisted Geopolymer Concrete Mix Design: A Step Towards Sustainable Construction. *International Conference on Artificial Intelligence of Things*; 2023: Springer. https://doi.org/10.1007/978-3-031-48781-1_26
- [50] Chouksey A, Verma M, Dev N, Rahman I, Upreti K. An investigation on the effect of curing conditions on the mechanical and microstructural properties of the geopolymer concrete. *Materials Research Express*. 2022;9(5):055003.
<https://doi.org/10.1088/2053-1591/ac6be0>
- [51] Poloju KK, Srinivasu K. Impact of GGBS and strength ratio on mechanical properties of geopolymer concrete under ambient curing and oven curing. *Materials Today: Proceedings*. 2021;42:962-8. <https://doi.org/10.1016/j.matpr.2020.11.934>
- [52] Gholampour A, Ozbakkaloglu T, Ng C-T. Ambient and oven-cured geopolymer concretes under active confinement. *Construction and Building Materials*. 2019;228:116722. <https://doi.org/10.1016/j.conbuildmat.2019.116722>
- [53] Singh A, Sandhu V. Effects of alccofine and curing conditions on properties of low calcium fly ash-based geopolymer concrete. *Materials Today: Proceedings*. 2020;32:620-5. <https://doi.org/10.1016/j.matpr.2020.02.763>
- [54] Suresh K, Muthukannan M, Arun K, Chithambar G, Kanniga D. Influence of incinerated biomedical waste ash and waste glass powder on the mechanical and flexural properties of reinforced geopolymer concrete. *Australian Journal of Structural Engineering*. 2022;23(3).
- [55] DiÅŸi E, Polat R. The influence of nano-CaO and nano-Al₂O₃ and curing conditions on perlite based geopolymer concrete produced by the one-part mixing method. *Construction and Building Materials*. 2022;346:128484.
<https://doi.org/10.1016/j.conbuildmat.2022.128484>
- [56] Arunkumar K, Muthukannan M, Sureshkumar A, Chithambarganesh A, Devi RK. Mechanical and durability characterization of hybrid fibre reinforced green geopolymer concrete. *Research on Engineering Structures and Materials*. 2022;8(1):19-43.
- [57] Saif MS, El-Hariri MOR, Sarie-Eldin AI, Tayeh BA, Farag MF. Impact of Ca⁺ content and curing condition on durability performance of metakaolin-based geopolymer mortars.

- Case Studies in Construction Materials. 2022;16:e00922. <https://doi.org/10.1016/j.cscm.2022.e00922>
- [58] Noushini A, Castel A. The effect of heat-curing on transport properties of low-calcium fly ash-based geopolymer concrete. *Construction and Building Materials*. 2016;112:464-77. <https://doi.org/10.1016/j.conbuildmat.2016.02.210>
- [59] Gunasekara C, Dirgantara R, Law DW, Setunge S. Effect of curing conditions on microstructure and pore-structure of brown coal fly ash geopolymers. *Applied Sciences*. 2019;9(15):3138. <https://doi.org/10.3390/app9153138>
- [60] Azarsa P, Gupta R. Comparative study involving effect of curing regime on elastic modulus of geopolymer concrete. *Buildings*. 2020;10(6):101. <https://doi.org/10.3390/buildings10060101>
- [61] Hasnaoui A, Ghorbel E, Wardeh G. Effect of curing conditions on the performance of geopolymer concrete based on granulated blast furnace slag and metakaolin. *Journal of Materials in Civil Engineering*. 2021;33(3):04020501. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003606](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003606)
- [62] Muthukrishnan S, Ramakrishnan S, Sanjayan J, editors. Buildability of geopolymer concrete for 3D printing with microwave heating. *Second RILEM International Conference on Concrete and Digital Fabrication: Digital Concrete 2020*. https://doi.org/10.1007/978-3-030-49916-7_90
- [63] Gholampour A, Ozbakkaloglu T. Oven-cured alkali-activated concrete. *Handbook of advances in Alkali-activated Concrete: Elsevier*; 2022; 157-86. <https://doi.org/10.1016/B978-0-323-85469-6.00019-2>
- [64] Ghafoor MT, Khan QS, Qazi AU, Sheikh MN, Hadi M. Influence of alkaline activators on the mechanical properties of fly ash based geopolymer concrete cured at ambient temperature. *Construction and Building Materials*. 2021;273:121752. <https://doi.org/10.1016/j.conbuildmat.2020.121752>
- [65] Cheng H, Lin K-L, Cui R, Hwang C-L, Chang Y-M, Cheng T-W. The effects of SiO₂/Na₂O molar ratio on the characteristics of alkali-activated waste catalystâ€"metakaolin based geopolymers. *Construction and Building Materials*. 2015;95:710-20. <https://doi.org/10.1016/j.conbuildmat.2015.07.028>
- [66] Amran M, Debbarma S, Ozbakkaloglu T. Fly ash-based eco-friendly geopolymer concrete: A critical review of the long-term durability properties. *Construction and Building Materials*. 2021;270:121857. <https://doi.org/10.1016/j.conbuildmat.2020.121857>
- [67] Alyousef R, Ebid AAK, Huseien GF, Mohammadhosseini H, Alabduljabbar H, Poi Ngian S, et al. Effects of Sulfate and Sulfuric Acid on Efficiency of Geopolymers as Concrete Repair Materials. *Gels*. 2022;8(1):53. <https://doi.org/10.3390/gels8010053>
- [68] Kumar R, Verma M, Dev N. Investigation on the effect of seawater condition, sulphate attack, acid attack, freezeâ€"thaw condition, and wettingâ€"drying on the geopolymer concrete. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*. 2022;1-31.
- [69] Valencia-Saavedra WG, de Gutierrez RM, Puertas F. Performance of FA-based geopolymer concretes exposed to acetic and sulfuric acids. *Construction and Building Materials*. 2020;257:119503. <https://doi.org/10.1016/j.conbuildmat.2020.119503>
- [70] Yang W, Zhu P, Liu H, Wang X, Ge W, Hua M. Resistance to sulfuric acid corrosion of geopolymer concrete based on different binding materials and alkali concentrations. *Materials*. 2021;14(23):7109. <https://doi.org/10.3390/ma14237109>
- [71] Pham TM, Lim YY, Malekzadeh M. Effect of pre-treatment methods of crumb rubber on strength, permeability and acid attack resistance of rubberised geopolymer concrete. *Journal of Building Engineering*. 2021;41:102448. <https://doi.org/10.1016/j.jobe.2021.102448>

- [72] Parathi S, Nagarajan P, Pallikkara SA. Ecofriendly geopolymers concrete: A comprehensive review. *Clean Technologies and Environmental Policy*. 2021;23:1701-13. <https://doi.org/10.1007/s10098-021-02085-0>
- [73] Srinivas T, Rao NR. Studies on the behaviour of sulphate attack resistance of low calcium fly ash and slag based geopolymer concrete. *IJCIET*. 2019;10(02):510-8.
- [74] Kanaan D, Soliman AM, Safhi AeM. External Sulfate Attack of Ambient-Cured One-Part Alkali-Activated Self-Consolidating Concrete. *Sustainability*. 2023;15(5):4127. <https://doi.org/10.3390/su15054127>
- [75] Singh RP, Vanapalli KR, Jadda K, Mohanty B. Durability assessment of fly ash, GGBS, and silica fume based geopolymer concrete with recycled aggregates against acid and sulfate attack. *Journal of Building Engineering*. 2023:108354. <https://doi.org/10.1016/j.jobe.2023.108354>
- [76] Ralli ZG, Pantazopoulou SJ. State of the art on geopolymer concrete. *International Journal of Structural Integrity*. 2021;12(4):511-33. <https://doi.org/10.1108/IJSI-05-2020-0050>
- [77] Ugurlu Al^o, Karakoç MB, Özcan A. Effect of binder content and recycled concrete aggregate on freeze-thaw and sulfate resistance of GGBFS based geopolymer concretes. *Construction and Building Materials*. 2021;301:124246. <https://doi.org/10.1016/j.conbuildmat.2021.124246>
- [78] Guo L, Wu Y, Xu F, Song X, Ye J, Duan P, et al. Sulfate resistance of hybrid fiber reinforced metakaolin geopolymer composites. *Composites Part B: Engineering*. 2020;183:107689. <https://doi.org/10.1016/j.compositesb.2019.107689>
- [79] Guo X, Xiong G. Resistance of fiber-reinforced fly ash-steel slag based geopolymer mortar to sulfate attack and drying-wetting cycles. *Construction and Building Materials*. 2021;269:121326. <https://doi.org/10.1016/j.conbuildmat.2020.121326>
- [80] Kuri JC, Nuruzzaman M, Sarker PK. Sodium sulphate resistance of geopolymer mortar produced using ground ferronickel slag with fly ash. *Ceramics International*. 2023;49(2):2765-73. <https://doi.org/10.1016/j.ceramint.2022.09.258>
- [81] Duan X, Yang S, Waclawek S, Fang G, Xiao R, Dionysiou DD. Limitations and prospects of sulfate-radical based advanced oxidation processes. *Journal of Environmental Chemical Engineering*. 2020;8(4):103849. <https://doi.org/10.1016/j.jece.2020.103849>
- [82] Zhuang Z, Mu S, Guo Z, Liu G, Zhang J, Miao C. Diffusion-reaction models for concrete exposed to chloride-sulfate attack based on porosity and water saturation. *Cement and Concrete Composites*. 2023:105378. <https://doi.org/10.1016/j.cemconcomp.2023.105378>
- [83] Lingyu T, Dongpo H, Jianing Z, Hongguang W. Durability of geopolymers and geopolymer concretes: A review. *Reviews on Advanced Materials Science*. 2021;60(1):1-14. <https://doi.org/10.1515/rams-2021-0002>
- [84] Nasir M, Johari MAM, Maslehuddin M, Yusuf MO. Sodium sulfate resistance of alkali/slag activated silico-manganese fume-based composites. *Structural Concrete*. 2021;22:E415-E29. <https://doi.org/10.1002/suco.202000079>
- [85] Hassan A, Arif M, Shariq M. Influence of microstructure of geopolymer concrete on its mechanical properties—A review. *Advances in Sustainable Construction Materials and Geotechnical Engineering: Select Proceedings of TRACE 2018*. 2020:119-29. https://doi.org/10.1007/978-981-13-7480-7_10
- [86] Milla J, Cavalline TL, Rupnow TD, Melugiri-Shankaramurthy B, Wang K, Lomboy G. Methods of test for concrete permeability: a critical review. *Advances in Civil Engineering Materials*. 2021;10(1):172-209. <https://doi.org/10.1520/ACEM20200067>
- [87] Ross JH, Genedy M, Juenger MC, van Oort E. Permeability recovery by self-healing of class F fly ash-based geopolymers. *Cement*. 2022;10:100048. <https://doi.org/10.1016/j.cement.2022.100048>

- [88] Nasvi M, Ranjith P, Sanjayan J. The permeability of geopolymers at down-hole stress conditions: Application for carbon dioxide sequestration wells. *Applied energy*. 2013;102:1391-8. <https://doi.org/10.1016/j.apenergy.2012.09.004>
- [89] Arafa S, Milad A, Yusoff NIM, Al-Ansari N, Yaseen ZM. Investigation into the permeability and strength of pervious geopolymer concrete containing coated biomass aggregate material. *Journal of materials research and technology*. 2021;15:2075-87. <https://doi.org/10.1016/j.jmrt.2021.09.045>
- [90] Zhang X, Zhang X, Li X, Tian D, Ma M, Wang T. Optimized pore structure and high permeability of metakaolin/fly-ash-based geopolymer foams from Al- and H₂O₂-sodium oleate foaming systems. *Ceramics International*. 2022;48(13):18348-60. <https://doi.org/10.1016/j.ceramint.2022.03.094>
- [91] Hassan A, Arif M, Shariq M, Alomayri T, Pereira S. Fire resistance characteristics of geopolymer concrete for environmental sustainability: a review of thermal, mechanical and microstructure properties. *Environment, Development and Sustainability*. 2023;25(9):8975-9010. <https://doi.org/10.1007/s10668-022-02495-0>
- [92] Alhamad A, Yehia S, Lubal³y Å%, Elchalakani M. Performance of different concrete types exposed to elevated temperatures: a review. *Materials*. 2022;15(14):5032. <https://doi.org/10.3390/ma15145032>
- [93] Ma G, Jia K, Xie P, Ruhan A, Wang L, Ding X, et al. Physical, mineralogical, thermal, and mechanical properties of aerogel-incorporated concrete exposed to elevated temperatures. *Cement and Concrete Composites*. 2023;140:105089. <https://doi.org/10.1016/j.cemconcomp.2023.105089>
- [94] Kong DL, Sanjayan JG. Damage behavior of geopolymer composites exposed to elevated temperatures. *Cement and Concrete Composites*. 2008;30(10):986-91. <https://doi.org/10.1016/j.cemconcomp.2008.08.001>
- [95] Wang J, Chen X, Li C, Zhou Z, Du P, Zhang X. Evaluating the effect of kaliophilite on the fire resistance of geopolymer concrete. *Journal of Building Engineering*. 2023:106975. <https://doi.org/10.1016/j.jobe.2023.106975>
- [96] Nuaklong P, Worawatnalunart P, Jongvivatsakul P, Tangaramvong S, Pothisiri T, Likitlersuang S. Pre- and post-fire mechanical performances of high calcium fly ash geopolymer concrete containing granite waste. *Journal of Building Engineering*. 2021;44:103265. <https://doi.org/10.1016/j.jobe.2021.103265>
- [97] Abd Razak SN, Shafiq N, Nikbakht EH, Mohammed BS, Guillaumat L, Farhan SA. Fire performance of fly-ash-based geopolymer concrete: Effect of burning temperature on mechanical and microstructural properties. *Materials Today: Proceedings*. 2022;66:2665-9. <https://doi.org/10.1016/j.matpr.2022.06.491>
- [98] Nuaklong P, Jongvivatsakul P, Pothisiri T, Sata V, Chindaprasirt P. Influence of rice husk ash on mechanical properties and fire resistance of recycled aggregate high-calcium fly ash geopolymer concrete. *Journal of Cleaner Production*. 2020;252:119797. <https://doi.org/10.1016/j.jclepro.2019.119797>
- [99] Okoye FN, Prakash S, Singh NB. Durability of fly ash based geopolymer concrete in the presence of silica fume. *Journal of cleaner Production*. 2017;149:1062-7. <https://doi.org/10.1016/j.jclepro.2017.02.176>
- [100] Chindaprasirt P, Chalee W. Effect of sodium hydroxide concentration on chloride penetration and steel corrosion of fly ash-based geopolymer concrete under marine site. *Construction and building materials*. 2014;63:303-10. <https://doi.org/10.1016/j.conbuildmat.2014.04.010>
- [101] Halim LN, Ekaputri JJ, editors. The influence of salt water on chloride penetration in geopolymer concrete. *MATEC Web of Conferences*; 2017: EDP Sciences. <https://doi.org/10.1051/mateconf/20179701002>
- [102] Ahmed MF, Khalil WI, Frayyeh QJ. Effect of waste clay brick on the modulus of elasticity, drying shrinkage and microstructure of metakaolin-based geopolymer

- concrete. *Arabian Journal for Science and Engineering*. 2022;47(10):12671-83. <https://doi.org/10.1007/s13369-022-06611-0>
- [103] Ridtirud C, Chindaprasirt P, Pimraksa K. Factors affecting the shrinkage of fly ash geopolymers. *International Journal of Minerals, Metallurgy, and Materials*. 2011;18(1):100-4. <https://doi.org/10.1007/s12613-011-0407-z>
- [104] Neupane K, Kidd P, Chalmers D, Baweja D, Shrestha R. Investigation on compressive strength development and drying shrinkage of ambient cured powder-activated geopolymer concretes. *Australian Journal of Civil Engineering*. 2016;14(1):72-83. <https://doi.org/10.1080/14488353.2016.1163765>
- [105] Grengg C, Ukrainczyk N, Koraimann G, Mueller B, Dietzel M, Mittermayr F. Long-term in situ performance of geopolymer, calcium aluminate and Portland cement-based materials exposed to microbially induced acid corrosion. *Cement and Concrete Research*. 2020;131:106034. <https://doi.org/10.1016/j.cemconres.2020.106034>
- [106] Law DW, Adam AA, Molyneaux TK, Patnaikuni I, Wardhono A. Long term durability properties of class F fly ash geopolymer concrete. *Materials and Structures*. 2015;48:721-31. <https://doi.org/10.1617/s11527-014-0268-9>
- [107] Zhuguo L, Sha L. Carbonation resistance of fly ash and blast furnace slag based geopolymer concrete. *Construction and Building Materials*. 2018;163:668-80. <https://doi.org/10.1016/j.conbuildmat.2017.12.127>
- [108] Pasupathy K, Berndt M, Castel A, Sanjayan J, Pathmanathan R. Carbonation of a blended slag-fly ash geopolymer concrete in field conditions after 8 years. *Construction and Building Materials*. 2016;125:661-9. <https://doi.org/10.1016/j.conbuildmat.2016.08.078>