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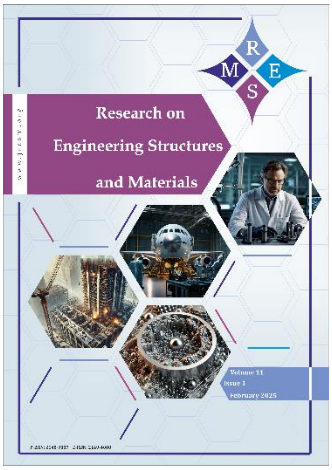

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Review Article

Factors affecting durability properties of GPC: A review

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Abstract

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.

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 (CO_2) 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

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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].

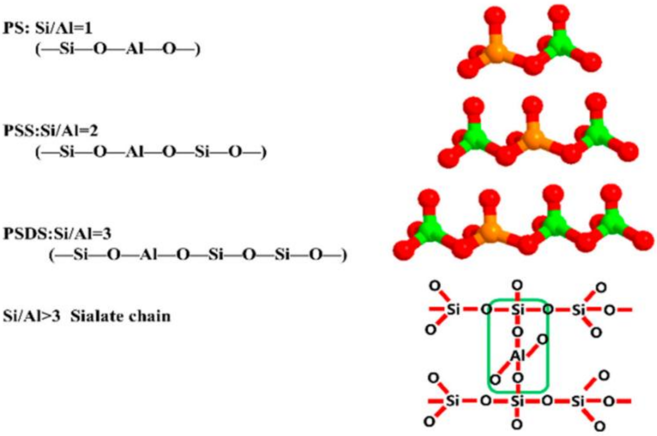

Fig. 1. Model of Geopolymer with various Si/Al molars [33]

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.

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.

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

Ref	Binder	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	P_2O_5	K_2O	Na_2O	TIO_2	L.O.I	SO_3
Jindal et al. [40]	RHA	90	0.46	0.43	1.10	0.77	NA	4.6	NA	NA	3.9	NA
	Ultra-fine slag (UFS)	33.9	22.6	1.4	32.8	7.8	NA	NA	NA	NA	NA	0.23
Albegmprli 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 Sarvandani [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

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_2SiO_3	GPC samples cured by oven show a somewhat higher strength than that of GPC cured by ambient condition.
Singh and Sandhu [53]	27 and 90 C	Fly Ash and Alccofine	NaOH and Na_2SiO_3	GPC samples have improved properties at 27 and 90 °C owing to the creation of polymer and hydration products.
Suresh et al. [54]	Ambient curing	GGBS and bio-medical waste ash	NaOH and Na_2SiO_3	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
Dişçi and Polat [55]	heat + water cured and heat + ambient 90 C for 72.	Perlite, Nano-CaO, and Nano-Al2O3	NaOH and Na_2SiO_3	The compressive strength and durability of GPC improved in the heat curing condition than the ambient curing condition.
Poloju and Srinivasu [51]	Ambient curing and Oven curing with 60C	GGBS and fly ash	NaOH and Na_2SiO_3	The samples of GPC oven-cured recorded better performance compared to GPC samples that cured at ambient condition
Arunkumar et al. [56]	Ambient curing	Fly ash and waste wood ash	NaOH and Na_2SiO_3	Addition of waste wood ash as fly ash replacement and waste rubber tires as a fiber at ambient curing enhanced the GPC properties.
Wang et al. [48]	20, 40, 60, 80 and 100 °C	GGBS and fly ash	NaOH and Na_2SiO_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.

Saif et al. [57]	ambient curing and 60 °C heat curing	Fly ash, GGBS, and mtakaolin	NaOH and Na_2SiO_3	Heat curing enhance the durability 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_2SiO_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 (Na_2SiO_3) and sodium hydroxide (NaOH) [64]. The chemical composition can be represented as: Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3), 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 Na_2O to SiO_2 in sodium silicate (Na_2SiO_3) 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 Na_2O 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 H2SO4, 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.

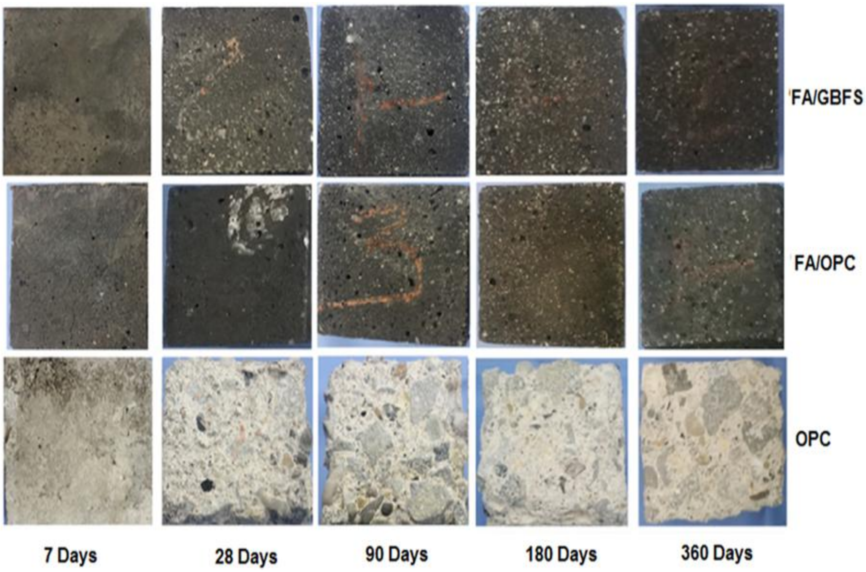

Fig. 2. Appearance of concrete samples exposed to H_2SO_4 for different periods [69]

Table 3. Resistance of geopolymer against acid attacks

References	Type of acid	Aluminosilicate	Alkali activator	Effect on the GPC
Albegmprli et al., [41]	H_2SO_4% in 0, 5, and 10%	GGBS, fly ash, and cement	NaOH and Na_2SiO_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_2SO_4, especially at a concentration of 10%.

Valencia-Saavedra et al., [69]	Acetic acid (CH_3-COOH) and sulfuric acid (H_2SO_4)	Fly ash, GGBS, and cement	NaOH and Na_2SiO_3	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%.
Yang et al. [70]	H_2SO_4	Metakaolin and fly ash	NaOH and Na_2SiO_3	Minor deterioration was noted for samples of GPC exposed to H_2SO_4 in terms of mass loss, neutralization depth, and visual appearance.
Pham et al. [71]	H_2SO_4	Ultrafine slag, cement, and fly ash	NaOH and Na_2SiO_3	GPC with crumb rubber showed poorer resistance to acid attacks (H_2SO_4 and HCl).

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.

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].

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.

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	Aliminosilicate	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 ± 0.09 µD at 28 curing days.
Nasvi et al. [88]	Fly ash	Na_2SiO_3 and NaOH	The permeability of GPC decreases due to increase of confining Pressure and decrease the connectivity of pores.
Arafa et al. [89]	Fly ash	Na_2SiO_3 and NaOH	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.
Zhang et al. [90]	MK and fly ash	Na_2SiO_3 and NaOH	The permeability siginificant affected by the pore connectivity, pore size, and porosity of the GP foam concrete.

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 $Ca(OH)_2$ into CaO, there is an observed increase in pore volume and surface area.

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_2SO_4	The addition of kaliophilite significantly enhanced the resistance against fire of GPC samples.
Nuaklong et al. [96]	Fly ash	NaOH and Na_2SO_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_2SO_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_2SO_4	

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. 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.

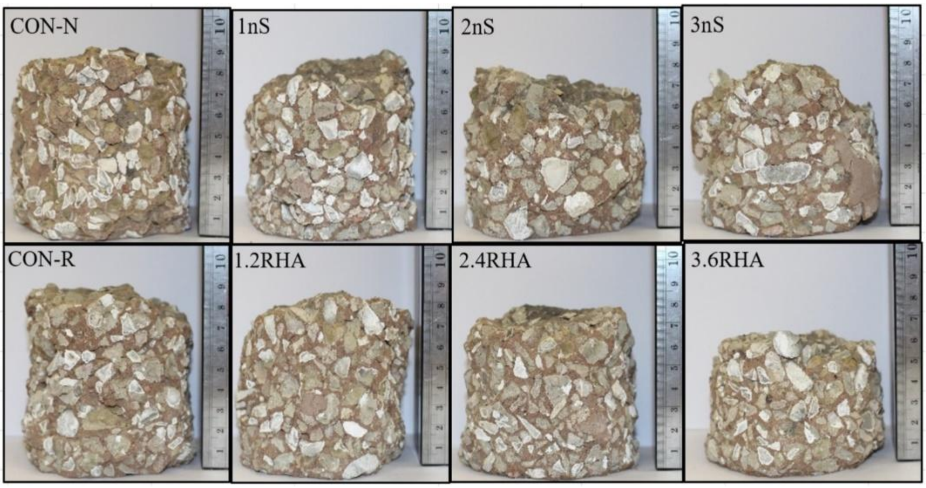

Fig. 3. Shape of fire-damaged samples exposed to fire for 90 minutes [98]

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, H_2SO_4 (pH=3, and 10% $MgSO_4$) 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 (H_2SO_4) 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.

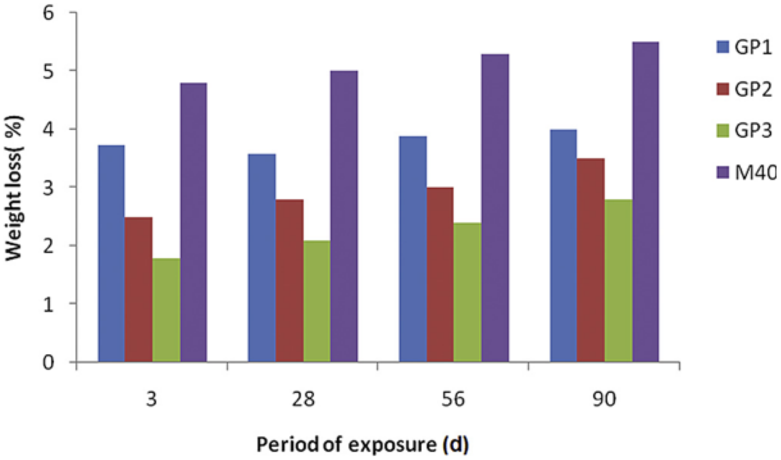

Fig. 4. Weight loss vs exposure periods for GPC and M40 samples in 5% NaCl [99]

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.

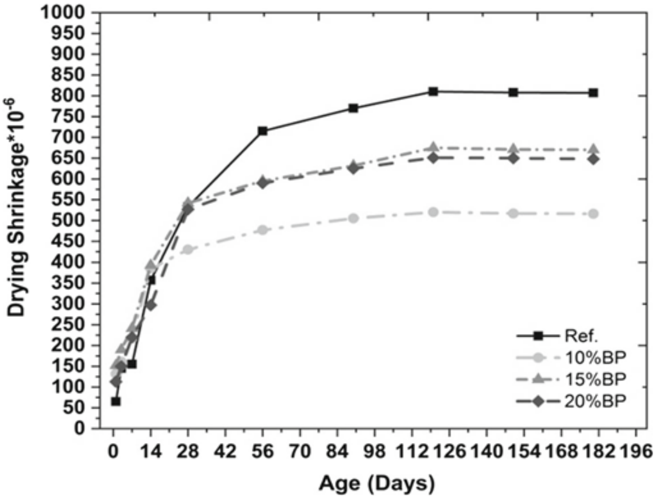

Fig. 5 Effect of clay brick waste powder (BP) on the drying shrinkage of GPC [102]

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. Ridtirud 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 CO_2 with sodium hydroxide (NaOH) making sodium carbonate $NaCO_3$ + 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 Na_2SiO_3 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 Na_2SiO_3 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.

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