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Hydration, Microstructure, and Properties of Fly Ash–Based Geopolymer: A Review

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Geopolymers have gained attention as a potential eco-friendly alternative to Portland cement, primarily due to their reduced carbon dioxide emissions and the opportunity to repurpose industrial waste materials. Fly ash (FA), a byproduct of coal combustion, has been favored as a raw material for geopolymer concrete owing to its widespread availability and high concentrations of alumina and silica. The development and application of fly ash–based geopolymer concrete can contribute significantly to production of sustainable construction materials. An in-depth analysis of fly ash–based geopolymer concrete has been conducted to explore its potential as a substitute for traditional concrete. This review encompasses the underlying reaction mechanism, strength, long-term durability, and microstructural characteristics of geopolymer concrete. The present review paper shows that adding the optimal quantity of fly ash improves the performance of fly ash–based geopolymer when exposed to extreme durability conditions, as well as improving strength properties. The microstructural analysis shows that when fly ash is added, the microstructure of the concrete matrix would be dense and packed. However, challenges remain in adopting fly ash–based geopolymer concrete for large-scale construction projects, as the existing literature presents inconsistencies in the reported strength, durability, and test results. Further research is necessary to consolidate knowledge on the behavior and mechanism of fly ash–based geopolymer concrete and to ultimately provide comprehensive data to support its widespread implementation in the construction industry.

Keywords: *Hydration, Properties, Geopolymer Concrete, Microstructure, Fly Ash*

1. Introduction

Cement is a significant construction material utilized in the field construction sector due to its abundance, excellent binding, and strength characteristics [1, 2]. However, the process of Portland cement production causes emission of CO_2 in a significant amount [3], leading to severe problems for environmental well-being. Furthermore, materials incorporated into Portland cement get rusted due to CO_2 and corrosive ions in the air during the material's service life. This significantly impacts the durability and strength characteristics of buildings. Geopolymer concrete (GPC) is viewed as a suitable substitute for cement as an eco-efficient construction material due to the wide availability of its raw ingredients and excellent durability and strength properties [4–8]. Oxides formed by inorganic polycondensation with a 3-D network arrangement enhance GPC's strength. The steady network arrangement provides GPC with outstanding higher strength and durability and protects the service life of engineered buildings [9, 10]. Binder materials utilized in GPC can be classified into three types as per the proportion of calcium: high calcium, no calcium, and low calcium [9–15]. These binder materials are signified by granulated blast furnace slag (GBFS), metakaolin clay, and fly ash (FA), correspondingly. Xionan et al. [16] revealed that adding red mud and fly ash by 39% of volume helped achieve optimized geopolymer performance. GPC developed using metakaolin clay tends to have more durability and strength than concrete made with Portland cement [17]. Xionan et al. [18] noted that the inherent properties of different types of fly ash would impact the strength and microstructural characteristics of geopolymer concrete. The gels of calcium-silicate-hydrate and calcium-aluminate-silicate-hydrate, which have low ratios of calcium and silicate in the chemical reactions of alkali-activated products of GBFS, provide GBFS-

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based GPC that has good resistance to acid attack and also has higher mechanical properties [19]. Cuifang et al. [20] revealed that source materials of geopolymer would majorly influence the rheological property of alkali-activated materials. The gels of Fly Ash-based Geopolymer Concrete, which are enriched in alumina-silicates, provide enhanced strength characteristics in the primary curing phase [21]. Jian et al. [22] noted that the development rate of calcium carbonate is reduced when adding 6% of Na_2O with 60% GBFS to make geopolymer. Furthermore, the filling impact of FA particles on pores enhances the impenetrability of fly ash–based GPC. Generally, the method of making FA-based GPC is modest compared to GPC made with metakaolin clay [23, 24]. Yiwei et al. [25] showed that adding steel fibers in different quantities can improve geopolymer concrete brittleness. FA-based GPC experiences fewer distortions than GBFS-based GPC does in a similar environment during its service life. It could be concluded that FA-based GPC has excellent durability and strength performance [26–28]. It has been observed that supplementary cementitious materials and steel fibers could transform regular geopolymer concrete to ultra-high-performance GPC [29]. Massively utilizing FA-based GPC can decrease environmental contamination due to greenhouse gases due to lower levels of production and usage of Portland cement [30]. To summarize, FA-based GPC is utilized in the construction sector as a possible sustainable construction material for building structures [17, 31].

Significance of Present Paper

From the above literature review, the author noted that there is a limited number of studies examining the interrelated aspects of strength, long-term durability under harsh conditions, and microstructural properties of fly ash (FA)–based geopolymer concrete (GPC). Furthermore, the reported findings have been inconsistent across various attributes. It is essential to consolidate existing research to comprehensively evaluate the strength, durability, and microstructural properties of FA-based GPC. This paper aims to provide a comprehensive review of the mechanical properties (compressive strength, flexural strength, and split tensile strength) and long-term and extreme durability performance (resistance to freeze-thaw cycles, acid attack, chloride ingress, sulfate attack, carbonation attack, and high-temperature exposure) of FA-based GPC. In addition, the present paper will also discuss the microstructural characteristics of this material when subjected to extreme environmental conditions.

2. Chemical arrangement of fly ash–based geopolymer concrete

Raw ingredients of fly ash–based geopolymer concrete mainly comprises alkaline chemical solution, FA, water, and fine and coarse aggregates, as shown in Figure 1(a). Currently, slag and fly ash have been used in making geopolymer concrete due to their easy accessibility and rich amount of Al_2O_3 and SiO_2 [32]. Figure 1(b) shows the arrangement of Portland cement, fly ash, and slag correspondingly [33]. The chemical characteristics of fly ash and slag are very different, so the characteristics of geopolymer concrete utilizing various binders will be distinct [34]. The primary products of the reaction in fly ash and slag-based geopolymer concrete are the gel of calcium silicate hydrate (C-S-H), sodium aluminosilicate hydrate (N-A-S-H), and calcium aluminosilicate hydrate (C-A-S-H) [35]. FA and alkaline solution have a significant role in the strength, durability properties, and improving microstructure of the mix. The particle size and different FA types vary considerably [36]. The particle size of FA governs its chemical reactivity and solubility [37]. Still, the phase arrangement influences the sort and microstructural growth of alkali-activated reaction (AAR) products of fly ash–based GPC. Furthermore, the alkaline chemical solution considerably impacts gels' polymerization in AAR and gel's composition [31, 38–40]. The silicon proportion of an alkaline chemical solution significantly affects the characteristics of fly ash–based GPC. It could improve the strength of fly ash–based GPC by developing a substantial and packed pore structure. The outward structural steadiness of fly ash–based GPC is enhanced as the

soluble silicates in an alkaline chemical solution increase [21, 24, 31, 38–40].

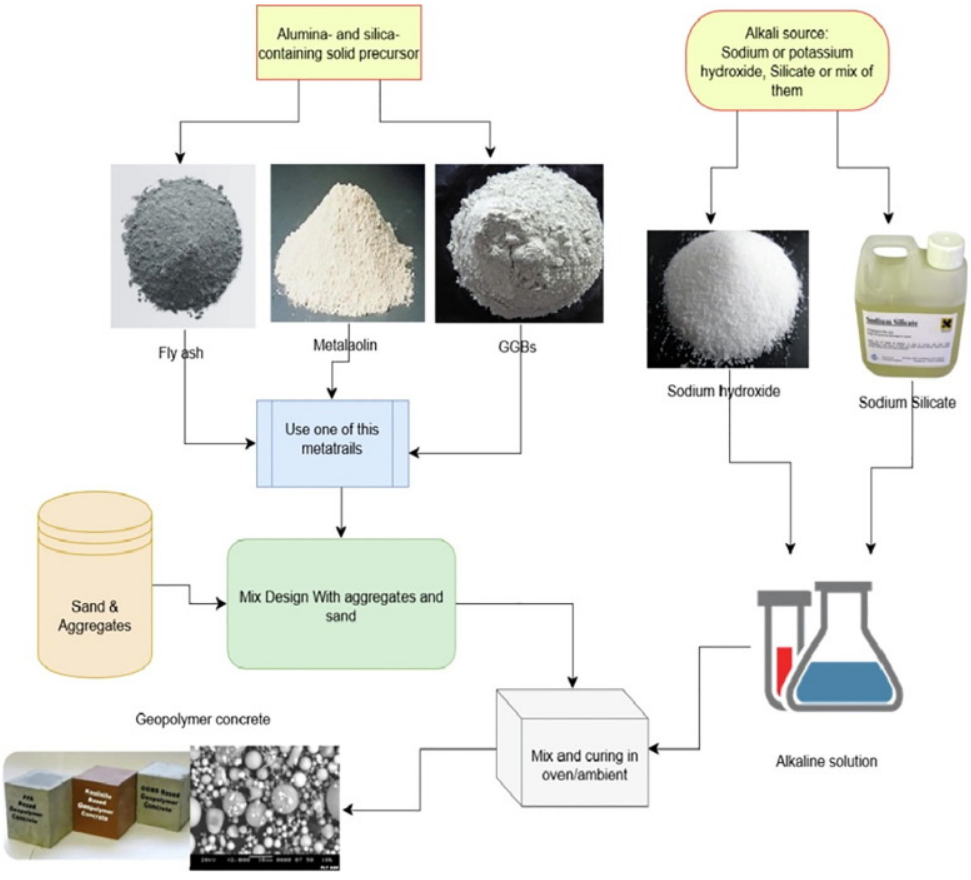
3. Characteristics of hardened FA-based GPC (compressive strength)

The compressive strength of concrete considerably influences the safety and stability of the structural system. Curing situations and raw ingredients impact the compressive strength of fly ash–based geopolymer concrete [43, 44]. Noushini et al. [45] developed low Ca fly ash–based geopolymer concrete utilizing twelve distinct thermal techniques of curing. Figure 2 depicts geopolymer concrete specimens' 28 day compressive strength at normal and temperature curing. Thermal curing considerably impacted the compressive strength of fly ash–based geopolymer concrete. In cured samples, the primary growth degree of compressive strength was raised with thermal curing and duration, and the optimum compressive strength was attained at 80°C [45]. This can be attributed both to thermal curing (with high temperature) and to extended periods of cure causing the development of extra products of reaction; hence with appropriate thermal curing, more ions of metals are added in the matrix of GPC, and the concentration of ions of metals is reduced [46]. Noushini et al. [45] studied the discharge of alkaline metals by evaluating the pH values for geopolymer mix. They noticed that the pH values of geopolymer under temperature curing were lesser than at room temperature [47]. The extreme alkalinity under curing at room temperature recommends a lesser grade of polymerization of specimens and decreased development of the resultant products. Hence, the compressive strength of fly ash–based GPC under room temperature curing was lesser [48].

By discussing the past literature, investigators can circumvent the influence of admixture on geopolymer concrete when performing the relevant experimental works in the future. Hence, these studies assist from an environmental point of view [49]. Bernal et al. [50] assessed the compressive strength of alkali silicate-activated concrete (AASC). It took the compressive strength of conventional concrete (OPCC) as a control for judgment. The compressive strength of alkali silicate-activated concrete and traditional concrete specimens with different amounts of binder (slag for AASC and cement for OPCC) is displayed in Figure 3.

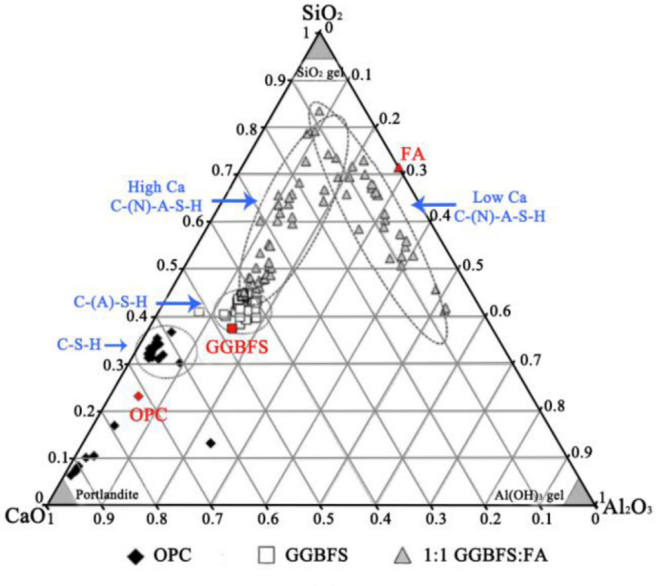
[51] studied the effects of basalt fibers on the compressive strength of FA-based GPC, as displayed in Figure 4. It was noticed that basalt fibers considerably raised the compressive strength of geopolymer concrete. Increasing the proportion of fibers raises the compressive strength and then reduces it. The optimum fiber amount was 2%. Furthermore, there was a minor distinction in the compressive strength of geopolymer concrete at between 28 and 7 days of cure. The enhancement in compressive strength of geopolymer concrete was significant because of the fiber's capability to convey load and stress. However, raising the proportion of fibers can't enhance the compressive strength uniformly [52]. This is uneven in past research on concrete with steel fibers [53]. It could be attributed to the high volume of fibers in the mix, which makes the mixture blend very hard and negatively influences the fresh properties of the mix.

Some research has been conducted on improving the mechanical characteristics of geopolymer concrete. Including nano-silica enhanced the compressive strength of geopolymer concrete [54], as shown in Figure 5. The compressive strength of geopolymer concrete was enhanced by adding 5% nano-silica. This was clarified as (a) the nano-silica had firm pozzolanic performance, and it improved the alteration of raw ingredients into gels of calcium-silicate-hydrate, sodium-aluminate-silicate-hydrate, and calcium-aluminate-silicate-hydrate (b) Particles of nano-silica had filling and nucleation impacts. Including 0.75% nano-silica decreased the compressive strength of geopolymer concrete, potentially due to the accretion of nanoparticles in the geopolymer matrix [55].



(A)

Fig. 1. (A): Raw ingredients used for the development of geopolymer concrete [41]



(B)

Fig. 1. (B): Composition of binder gel of Portland cement and geopolymer [42]

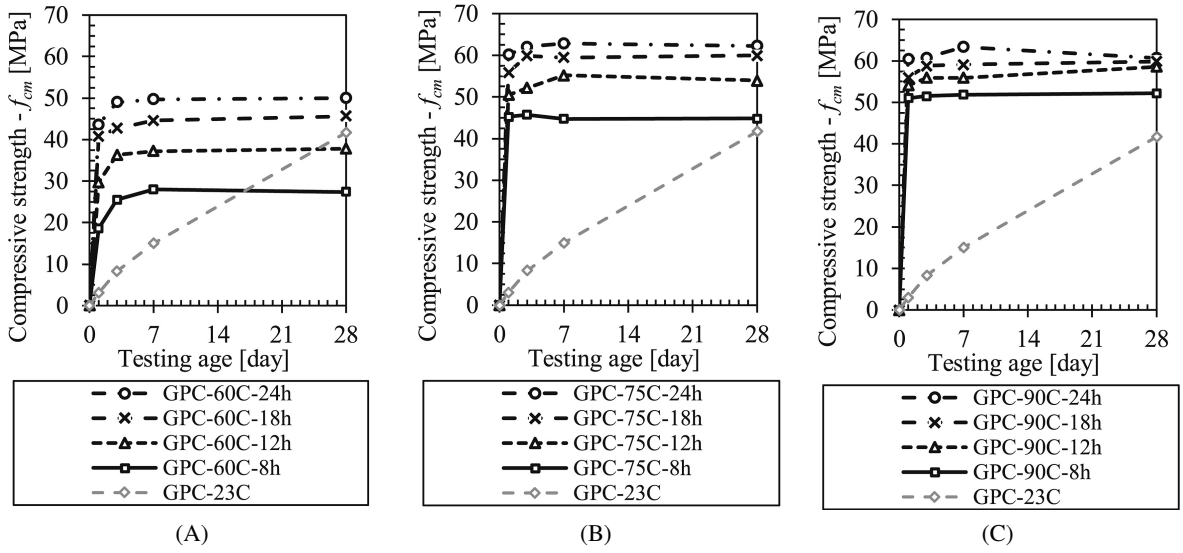


Fig. 2. Compressive strength of room temperature and thermally cured specimens [45]

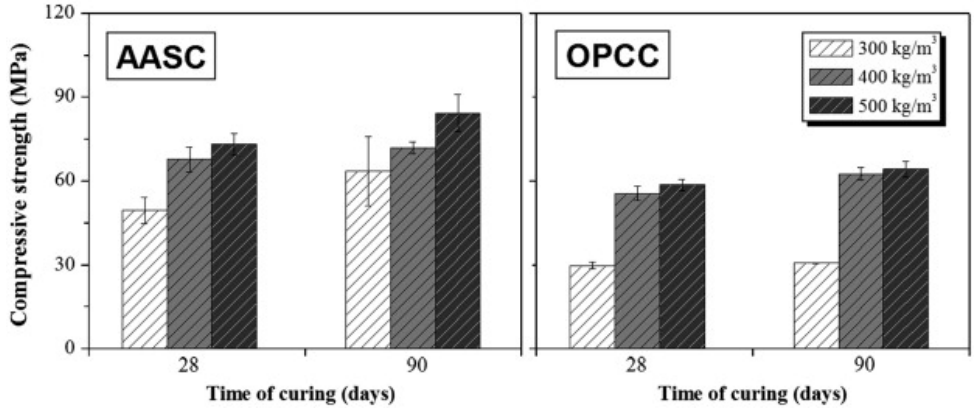


Fig. 3. Compressive strength of alkali silicate-activated concrete (left) and conventional concrete (right) [50]

4. Durability aspects of fly ash–based geopolymer concrete

4.1. Resistance to freeze and thaw

When the concrete specimen is frozen and thawed, repetitive seepage and expansion pressure are developed when extra water exists in the pores, leading to microscopic cracks and ultimately causing concrete failure [56]. The failure procedure under freeze and thaw for FA-based GPC is identical to conventional concrete. The freezing and thawing of FA-based GPC were observed by Skvara et al. [57]. It was noticed that after 150 rounds of freezing and thawing, the compressive strength of FA-based GPC was reduced slightly more than samples without any rounds of freezing and thawing. No visible failure or deformation caused by wear and tear was noticed. Sun et al. [58] contrasted the freezing and thawing resistance of FA-based GPC and conventional concrete of similar strength. It was revealed that after 300 rounds of freezing and thawing, the strength of FA-based GPC and traditional concrete reduced by 4.9% and 19.90%, correspondingly, and the decrease in mass was 0.21% and 1.38% (see Figure 6). This shows that FA-based GPC has more excellent resistance against

Table 1. Comparison and discussion based on freeze and thaw of FA-based GPC

Authors	Binding Material	Alkaline solution	Curing situation	Properties assessed	Result
Sun et al. [58]	Class F FA	Sodium silicate and sodium hydroxide	Curing of samples at 75°C for 12 hours	Freezing and thawing resistance of FA-based GP mortar and OPC mortar	FA-based GP mortar has incredible resistance to freezing and thawing than Portland cement mortar
Temujin et al. [60]	Class F FA	Sodium silicate and sodium hydroxide	Curing was done at a temperature of 75°C for 20 hours	Impact of calcium proportion on the behavior of FA-based GPC in freezing and thawing surroundings	FA-based GPC made with a high amount of calcium FA had less resistance against freezing and thawing
Zerzouri et al. [61]	Class F FA	Sodium silicate and sodium hydroxide	Curing at 65 – 85°C 4 to 10 hours	Resistance to freezing and thawing of FA-based GP mortar	FA-based GP mortar has incredible resistance to freezing and thawing
Zhao et al. [62]	Class F FA	Sodium silicate and sodium hydroxide	1, 7, 14, and 28 days curing at ambient temperature, 50 and 80 degrees	Impact of curing situations on durability against freezing and thawing of FA-based GPC	Enhancement in curing time and temperature can raise the development of geopolymer gel, which can enhance the structure of pores and further optimize the freezing and thawing resistance of GPC.

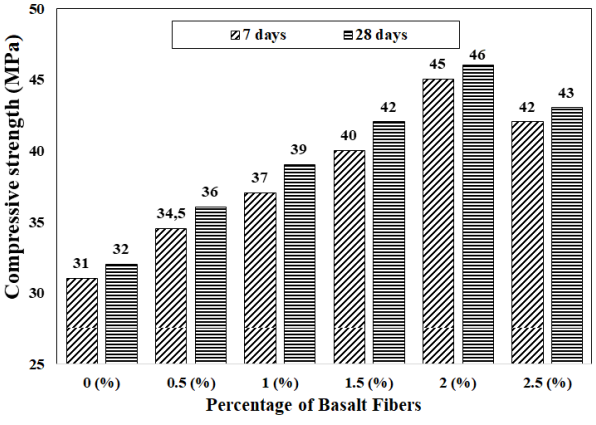


Fig. 4. Compressive strength of geopolymer concrete with basalt fibers [51]

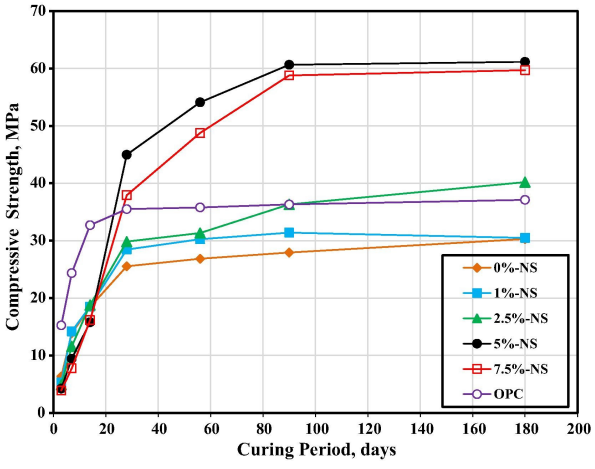


Fig. 5. Influence of the amount of Nano-silica on the specimen's compressive strength [54]

freezing and thawing than conventional concrete. Slavik et al. [59] researched freezing and thawing of GPC made with low calcium with burning bot-

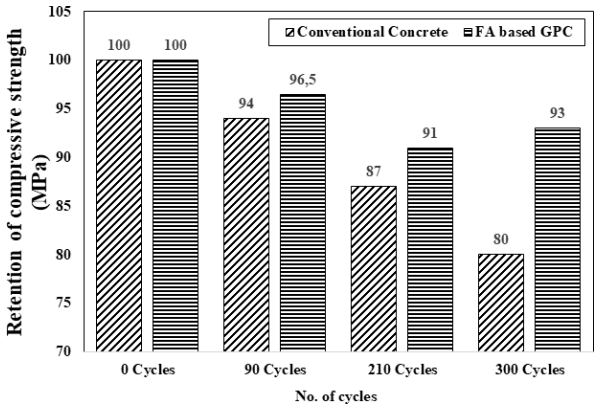


Fig. 6. Influence of different cycles of freezing and thawing on compressive strength of conventional concrete and FA-based GPC [58]

tom ash. They noticed that after 50 rounds of freezing and thawing, the sample's compressive strength was reduced by at least 19% compared to the control sample. The freezing and thawing resistance of FA-based GPC is relatively associated with pore water's permeability and filling rate. The amount of calcium, chemical arrangement of binder materials, and curing situations of FA affect ideal proportions of sodium-aluminate-silicate-hydrate and calcium- aluminate-silicate-hydrate gel with a filling of pores under different conditions. This impacts the freezing and thawing resistance of FA-based GPC. There are few variances in the study outcomes on freeze and thaw resistance for FA-based GPC. It is linked to multiple features, for instance: situations of curing and chemical arrangement of binder materials. The comparison and discussion on the resistance of FA-based GPC to freeze and thaw are presented in Table 1.

4.2. Resistance to acid attack

Reaction products formed from the alkaline chemical solution and the aluminum and calcium in non-hydrated raw ingredients in the sample dissolve into corrosive salts under acid environments. This instigates a quick reduction in the sample's strength and, ultimately, a reduction in the structure's service life [63]. The decrease in weight, and change in size and compressive strength of FA-based GPC in acid conditions are less than conventional concrete with identical grade strength. Furthermore, the sodium-aluminate-silicate-hydrate gel in reaction products of FA-based GPC formed from the alkaline solution is nearly non-soluble in acidic environments. Hence, FA-based GPC has more resistance to acid attacks than conventional concrete [64]. Arbi et al. [65] studied the compressive strength and mass of FA-based GPC, which decreased by 7.95 and 2.84%, correspondingly. Subsequently, it was dipped in 2% sulfuric acid for 4 weeks. Sathia et al. [66] contrasted the decrease rate in mass for FA-based GPC and conventional concrete with identical strength grades; subsequently, the sample was dipped in 3% sulfuric acid, it was revealed that the decrease rate in a mass of FA based GPC in the acid solution was considerably smaller in comparison to conventional concrete. Zerzouri et al. [61] observed the samples' level of wear and tear of FA-based

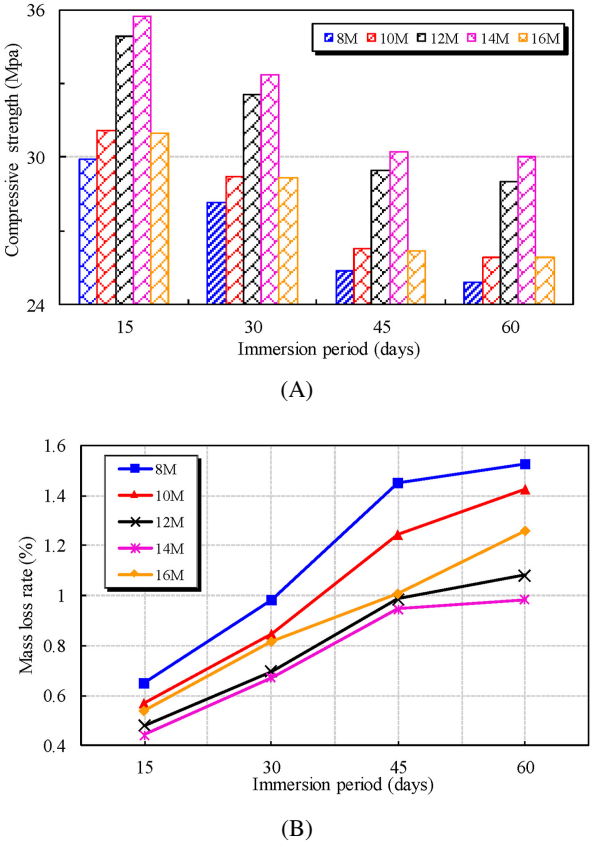


Fig. 7. (A) Compressive strength (B) rate of loss in mass of FA-based GPC due to acid attack [69]

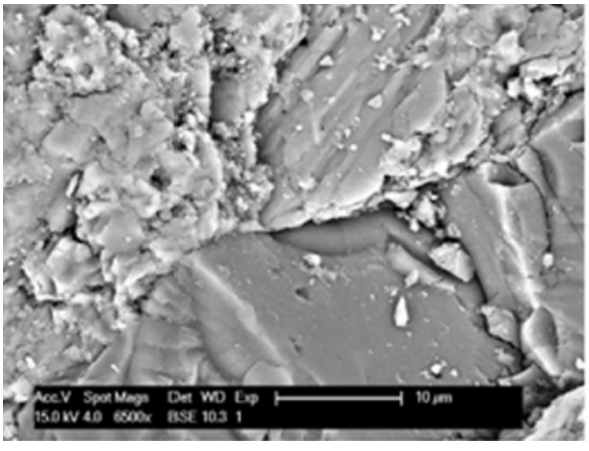
Table 2. Comparison and discussion based on acid resistance of FA-based GPC

Authors	Binding Material	Alkaline solution	Type of acid	Curing situation	Properties assessed	Result
Mehta et al. [71]	Class F FA	Sodium silicate and sodium hydroxide	5% sulfuric acid	Curing at a high temperature of 600°C in the oven for 1 day	Impact of sodium hydroxide on acid resistance of FA-based GPC	FA-based GPC made with a high concentration of sodium hydroxide had more resistance against acid
Lakhssassi et al. [61]	Class F FA	Sodium silicate and sodium hydroxide	3% sulfuric acid	Curing at 75°C for 1 day	Sulfuric acid resistance ofFA-based GPC and Portland cement concrete	Subsequently, ping in sulfuric acid
Bakharev et al. [61]	Class F FA	Sodium silicate, sodium hydroxide, and potassium hydroxide	Acetic acid	Curing for 1 day at ambient temperature, then sustained at 95°C for 1 day	Impact of alkaline solution on resistance of acid of FA-based GPC	Specimen made with sodium hydroxide had more resistance to acid. The inclusion of potassium hydroxide instigated a reduction in durability.
Ariffin et al. [67]	Class F FA	Sodium silicate and sodium hydroxide	3% sulfuric acid	Curing at a temperature of 28°C for 4 weeks	Resistance of GPC and Portland cement concrete against sulfuric acid	The sulfuric acid attack on FA-based GPC was excellent than the reference sample because of the stable firm microstructure of GPC
Wallah et al. [72]	Class F FA	Sodium silicate and sodium hydroxide	2% sulfuric acid	Curing was done at 65°C for 1 day	Resistance of FA-based GPC against the acid test	FA-based GPC has incredible resistance against acid attack

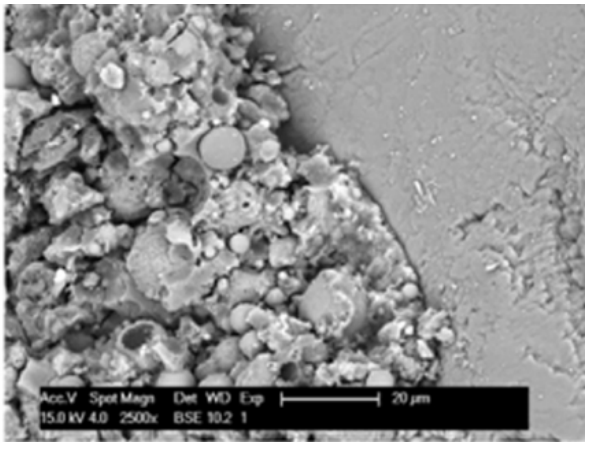
GPC and traditional concrete when placed in 5% sulfuric acid for 15 weeks. It was revealed that the surface of FA-based GPC deteriorated slightly, and the surface of conventional concrete was permeable and deteriorated significantly. Notably, the gel of calcium-silicate-hydrate decomposed to make a phase of gypsum and an ettringite. Ariffin et al. [67] contrasted the changes in compressive strength and sorts of corrosion products of FA-based GPC and conventional concrete dipped in 2% sulfuric acid for 80 weeks. It was revealed that the decrease in strength of FA-based GPC and traditional concrete was 40% and 70%, respectively. The Ca-rich gel of calcium-silicate-hydrate was dissolved and precip-

itated the gypsum stage after acid discharge. This led to control concrete with low strength and stability.

Moreover, the gel sodium-aluminate-silicate-hydrate in FA-based GPC didn't suffer considerable deterioration, and no sulfate precipitation was noticed. The significantly higher concentrations of alkaline solutions had a detrimental impact on the rust and acid resistance of the sample, however, as displayed in Figure 7. As per the research of Temmuujin et al. [68], it was revealed that FA-based GPC resistance against acid relies on the mineral arrangement of the level of geopolymerization of FA. Some minerals in FA generally don't contribute to the polymerization reaction: for instance, magnetite, maghemite, and hematite. They are vulnerable to corrosion and acid attack and dissolve to form extra pores. The Interfacial Transition Zone of the geopolymer concrete specimen's prior acid test displayed a tighter linking, as displayed in Figure 8; the morphology of the interfacial transition zone before and subsequent to dipping in a solution of sulfuric acid was considerably distinct, specifying that the interfacial transition zone in geopolymer concrete had enhanced resistance to acid attack in comparison to conventional concrete. The comparison and discussion of geopolymer concrete performance against acid attack is displayed in Table 2.



(A)



(B)

Fig. 8. Change in Interfacial Transition Zone of geopolymer concrete (A) before and (B) after the acid test [70]

4.3. Effect of chlorides on FA-based GPC

Alzeebaree et al. [73] studied the resistance of geopolymer concrete and conventional concrete against corrosion confined with fiber polymers under chloride attack. The test outcome specified the excellent conduct of geopolymer concrete with strands under periodic and stationary loads in different situations compared to conventional concrete. Confinement of geopolymer concrete with fibers improved outcomes for resistance against chlorides compared to traditional concrete. Furthermore, it was observed that the development of harmful ettringites in conventional concrete was greater, compared to geopolymer concrete, when subjected to the chloride test. Likewise, the longer period deformation for creep [74] and shrinkage

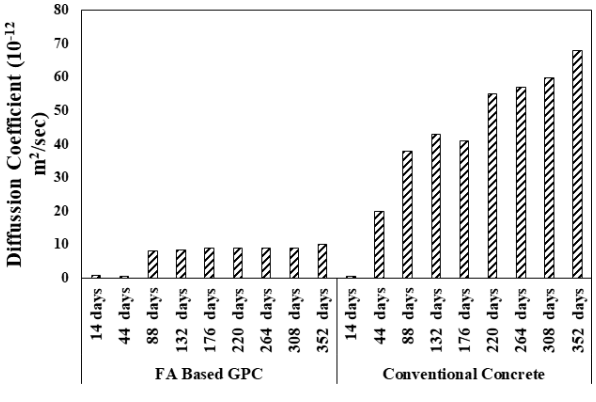


Fig. 9. Mean Coefficient of chloride diffusion for FA-based GPC and conventional concrete [69]

Table 3. Comparison and discussion of study based on chloride resistance of FA-based GPC

Authors	Binding Material	Alkaline solution	Curing situation	Properties assessed	Results
Yang et al. [78]	Class F FA and slag	Sodium silicate and sodium hydroxide	Curing was carried out at ambient condition	Influence of slag on the chloride resistance of FA-based GPC	Slag can assist in refining pore structure and thus decrease the sorptivity and avert the infiltration of chlorides into sample
Abdullah et al. [79]	Class F FA	Sodium silicate and sodium hydroxide	Curing was performed at ambient conditions for 1 day and then heat curing at 80°C	The chloride resistance of FA-based GPC was assessed.	FA-based GPC had excellent resistance to chloride as compared to conventional concrete.
Kupwade-Patil et al. [76]	Class F FA	Sodium silicate and sodium hydroxide	Temperature curing at 80°C for 3 days	Impact of Class F FA on chloride resistance of GPC and a reference concrete	GPC with class F FA had superior performance against chlorides than Portland cement concrete
Noushini et al. [45]	Class F FA	Sodium silicate and sodium hydroxide	Curing at 60, 75, and 90°C	Influence of curing situation on transport attributes, diffusion of chlorides, and binding of chlorides	Raise in the temperature of curing can decrease the coefficient of chlorides ion in FA-based GPC, Low Ca FA-based GPC had no capacity for binding chlorides.
Kannapiran et al. [80]	Class F FA	Sodium silicate and sodium hydroxide	Samples were cured at 75°C for 1 day	Resistance of chlorides for FA-based GPC	FA-based GPC had good resistance against chloride infiltration than reference concrete.

characteristics of unreinforced geopolymer concrete and reinforced geopolymer concrete with 1% fibers were evaluated [75]. Test outcomes showed an enhancement in the compressive strength of reinforced geopolymer concrete with strands compared to unreinforced geopolymer concrete. However, for many specimens, a considerable reduction in compressive strength was noticed.

Moreover, the strain for creep of fiber-reinforced geopolymer concrete depicted more strain in comparison to unreinforced geopolymer concrete, specifying poor conduct in creep loading for situations subjected to a longer period. Kupwade-Patil et al. [76] researched the durability of FA-based GPC and conventional concrete under chloride. They noted that the mean ions of chloride and coefficient of chloride diffusion of FA-based GPC were less than traditional concrete, as shown in Figure 9. FA-based GPC offered an improved level of resistance against penetration of chlorides and corrosion compared to conventional concrete [77]. This is possibly the outcome of the packed

matrix and improved microstructure of FA-based GPC. The comparison and discussion of geopolymer concrete performance against chloride is displayed in Table 3.

4.4. Resistance to sulfate attack

Evaluating corrosion due to sulfate attack is essential for understanding the wear and tear of concrete specimens. It includes sulfate ions diffusion [65], chemical reaction amid components of the sample and ions of sulfate, and changes in stress and distortion of the sample due to expansion [81]. The test outcome specified that the mechanism of attack due to sulfate on FA-based GPC and conventional concrete variates considerably, and FA-based GPC has more resistance against sulfate attack. In FA-based GPC, many aspects influence the attack of sulfate, for instance, the quantity of Ca in FA, sorts of sulfate solution, concentration, and types of alkaline chemical solution. The products of hydration – tri-calcium aluminate and tri-calcium silicate – in conventional concrete make gypsum and ettringite with sulfate. This causes deformation and failure in the specimen. The formation of gypsum causes the decalcification of a high quantity of calcium-silicate-hydrate gel, which makes the sample very soft. Moreover, part of the calcium-silicate-hydrate gel makes thaumasite in a sulfate solution. This causes a reduction in the sample's strength and increases deterioration [82]. FA-based GPC is more capable than conventional concrete regarding resistance to sulfate attack, primarily due to the cross-linked gel of silicate in FA-based GPC being very firm compared to the gel of calcium-silicate-hydrate. The arrangement of alumino-silicate gel is primarily unsoluble in a solution of sulfate.

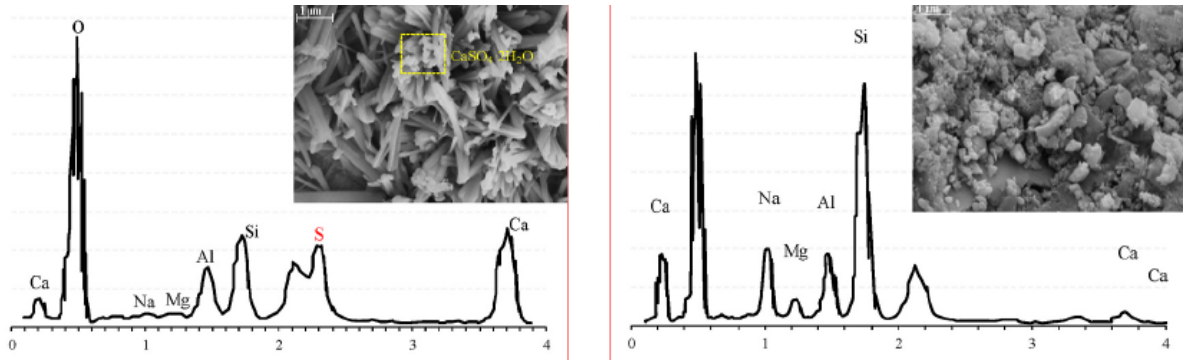
In contrast, a high quantity of calcium-silicate-hydrate gel in conventional concrete dissolves in a sulfate solution, and it is de-calcified to make ettringites. Bhutta et al. [83] noticed no visible failure on the surface of FA-based GPC when it was dipped in a 5% solution of sodium sulfate for 535 days. Moreover, there were some cracks in conventional concrete, and its mass and compressive strength decreased. Furthermore, electron dispersive X-ray analysis revealed the existence of the crystal structure of gypsum in conventional concrete. Scanning electron microscope (SEM) micrographs of FA-based GPC displayed that no new phase was shaped; the significant elements in electron dispersive X-ray analysis were oxygen, silica, sodium, and aluminum, as depicted in Figure 10. This shows that FA-based GPC displayed improved sulfate resistance compared to conventional concrete. Tang et al. [84] researched the resistance against sulfate of FA-based GPC and traditional concrete in similar sulfate surroundings. They noted that the compressive strength of FA-based GPC and traditional concrete changed, declining first and then rising. Furthermore, the decrease in the mass of conventional concrete was 0.55%, while the reduction of FA-based GPC was 0.25%. Long et al. researched the wear and tear mechanism of FA-based GPC and conventional concrete in a 5% magnesium sulfate solution. The Comparison and discussion of geopolymer concrete performance against sulfates is displayed in Table 4.

4.5. Resistance to carbonation attack

Carbonation in conventional concrete is a reaction between calcium hydroxide and carbon dioxide, which infiltrates the inner part of the concrete and causes calcium carbonate formation. The infiltration of carbon dioxide decreases concrete pH, reducing carbonation and removing the protecting coating around the reinforcement. This is a significant motivation for bars rusting in concrete. The carbonation mechanism for geopolymer concrete differs from conventional concrete, as shown in Figure 11. For high Ca geopolymer concrete, due to the absence of calcium hydroxide in polymerization products, the carbon dioxide in geopolymer concrete straight reacts with a gel of calcium-aluminate-silicate-hydrate, making calcium carbonate. Figure 12(a) displays the impact of the plastic cover and water curing on the carbonation depth of FA-based geopolymer concrete. The carbonization conduct of water-cured specimens was excellent compared to curing with a plastic cap. This can be attributed to the reaction of

Table 4. Comparison and discussion based on sulfate resistance of FA-based GPC

Authors	Binding Material	Alkaline solution	Sulfate solution	Properties assessed	Results
Elyamany et al. [85]	Class F FA	Sodium hydroxide	10% magnesium sulfate	Impacts of curing situation and alkaline solution on resistance of sulfates of FA-based GPC	Raising heat for curing causes a reduction in water absorption and the ratio of voids and improved resistance against magnesium sulfates.
Long et al. [86]	Class F FA	Sodium silicate and Sodium hydroxide	5% magnesium sulfate	Resistance against corrosion and related procedure of FA-based GPC and conventional concrete in an identical solution of sulfate	FA-based GPC had excellent resistance against magnesium sulfate compared to reference concrete due to its firm polymer alumino-silicate structure.
Bhutta et al. [83]	Class F FA	Sodium silicate and Sodium hydroxide	5% Sodium sulfate	Resistance of sulfate on FA-based GPC and a reference concrete	FA-based GPC had incredible conduct in 5% Sodium sulfate than Portland cement concrete because of its firm polymer alumino-silicate structure.
Ismail et al. [87]	Class F FA	Sodium silicate	5% Sodium sulfate and 5% magnesium sulfate	Impact of various sorts of sulfates on resistance against sulfate and corrosion attack of FA-based GPC	The existence of magnesium ions caused the de-calcification of the gel phase of rich calcium existing in FA-based GPC, which led to wear and tear of the binder. Magnesium sulfate could have harmful impacts on the sample.
Bakharev et al. [88]	Class F FA	Sodium silicate and Sodium hydroxide	5% Sodium sulfate and 5% magnesium sulfate	The durability of FA-based GPC in chemicals of Sodium sulfate and magnesium sulfate	The extent of corrosion in FA-based GPC is higher in magnesium sulfate than in sodium sulfate.



(A) (B)

Fig. 10. EDX analysis and SEM micrograph (A) conventional concrete, (B) FA-based GPC dipped in 5% solution of sodium sulfate [83]

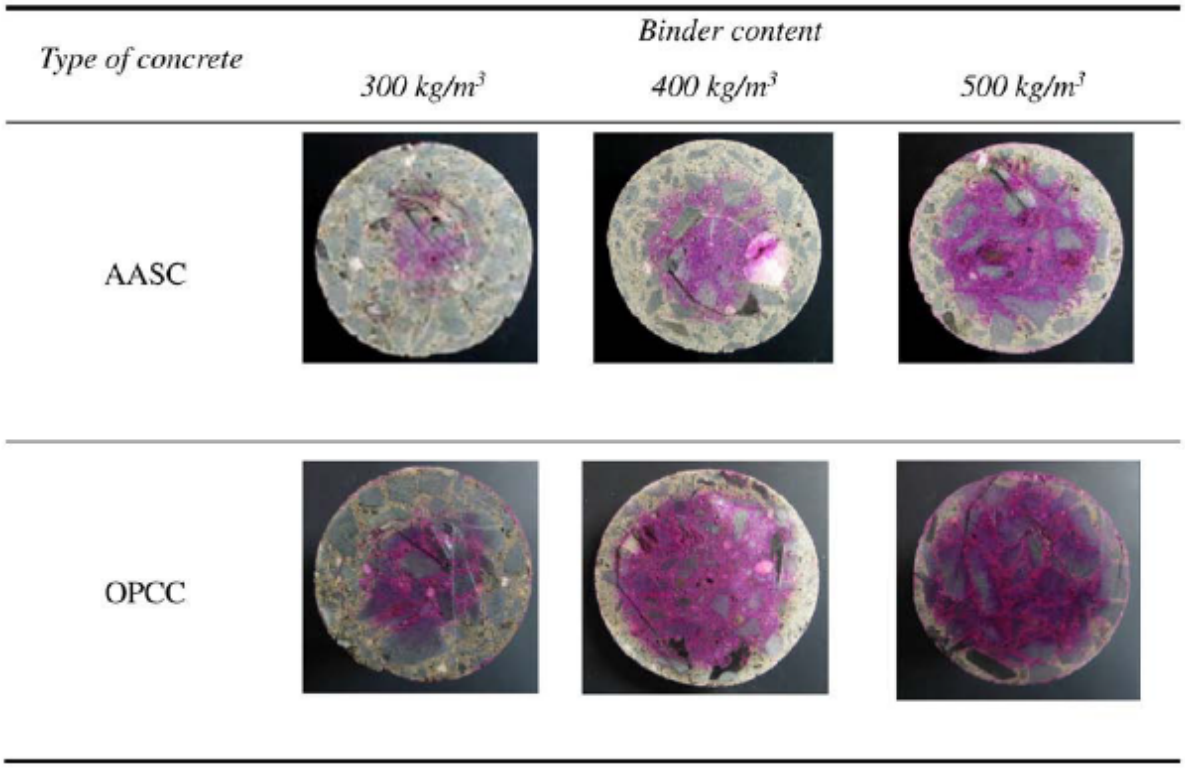
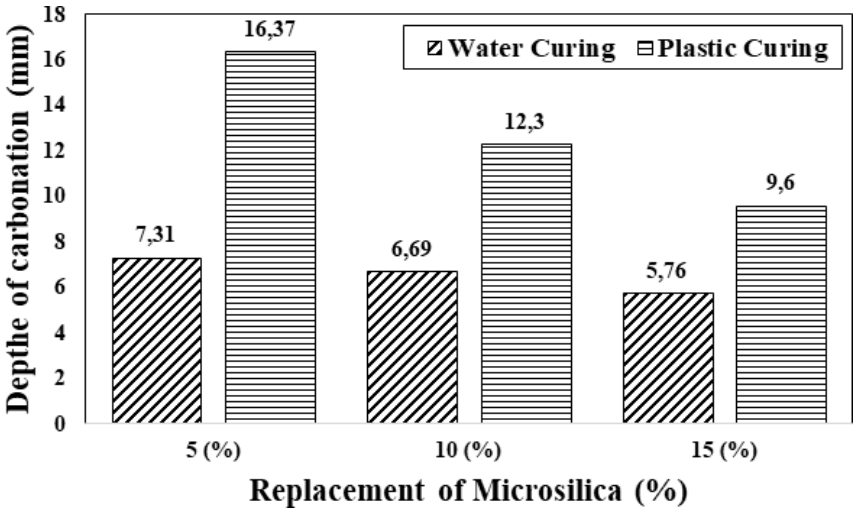


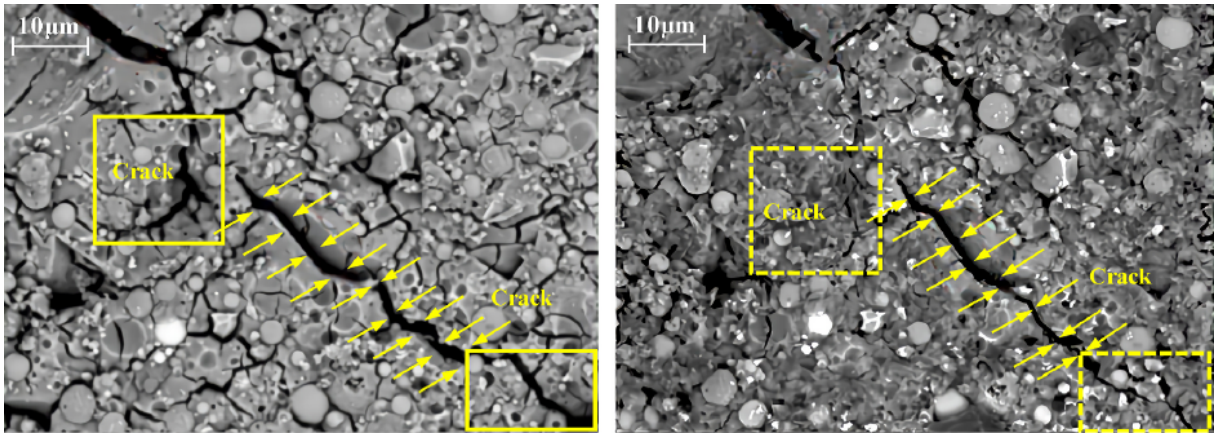
Fig. 11. Carbonation changes for geopolymer concrete and conventional concrete [50]

the binder with the required amount of water. Consequently, in the case when the water quantity is low, the gel would not consistently shape in the mix which results in low resistance to carbonation attack. Though, raising the amount of micro-SiO_2 can considerably optimize the carbonation conduct. Micro-SiO_2 has the perks of being smaller in size, the function of aggregates, and characteristics of volcanic ash; the substitution of FA with micro-SiO_2 had a good impact on the depth of carbonation of geopolymer concrete specimens [89]. It should be mentioned that there are different effects of micro-SiO_2 on the internal structures of FA-based geopolymer concrete and conventional concretes



(A)

Fig. 12. (A): Depth of carbonation of geopolymer concrete after 28 days [93]



(B)

Fig. 12. (B): Change in the microstructure of FA-based GPC before and after carbonation [90]

due to different chemical arrangements of fly ash and Portland cement, respectively. The number of micro-cracks in FA-based GPC decreased considerably, and the microstructure became dense, causing carbonization [90], as shown in Figure 12(b). The Comparison and discussion of geopolymer concrete performance against chloride is displayed in Table 5.

4.6. Resistance to high temperature

Geopolymer has a 3D zeolite-like internal arrangement that needs a lot of heat as compared to cement concrete to be damaged [96]. Hence, geopolymer concrete resists high temperatures [97]. With the help of testing, it could be established that geopolymer concrete can endure higher heat of a minimum of 750 to 900°C [98]. Figure 13 displays the variation in compressive strength for Portland cement concrete and fly ash–based geopolymer concrete showing the higher temperature varying from 30 to 1050°C [99]. The test outcome showed that the strength began to reduce with increasing heat. Still, the rate of strength reduction in fly ash–based geopolymer concrete was much slower than in Portland cement concrete, which specifies the higher resistance of fly ash–

Table 5. Comparison and discussion on carbonation resistance of FA-based GPC

Authors	Binding Material	Alkaline solution	Carbonation situation	Properties assessed	Results
Khan et al. [92]	Class F FA	Sodium silicate and sodium hydroxide	Quickened temperature for carbonation 23°C, humidity 50%, and 1% concentration of carbon dioxide	Impact of concentration of carbon dioxide on carbonation mechanism of GPC	Test outcome depicts that the rate of carbonation and depth of GPC raises considerably with raise in the concentration of carbon dioxide
Badar et al. [93]	Class F FA	Sodium silicate and sodium hydroxide	Quickened temperature for carbonation 24°C, humidity 65%, and 5% concentration of carbon dioxide	Impact of the amount of calcium on resistance against carbonation of FA-based GPC	Quickened carbonation tempted the reduction in pH, decrease in strength, and raise in permeability of FA-based GPC.
Bernal et al. [94]	Class F FA	Sodium silicate and sodium hydroxide	Quickened temperature for carbonation 23°C, humidity 65%, and 1% to 5% concentration of carbon dioxide	The variations in gel structure of FA-based GPC through the quickened carbonation mechanism.	The gel of sodium-aluminate-silicate-hydrate mainly was not changed. At the same time, the gel of calcium-aluminate-silicate-hydrate gets de-calcified to develop a firm pore structure.
Pasupathy et al. [95]	Class F FA and GBFS	Sodium silicate and sodium hydroxide	Natural carbonation	Impact of the proportion of slag on resistance against carbonation of FA-based GPC	The inclusion of GBFS could decrease the permeability and pore diameter of GPC, which can reduce the rate of diffusion of carbon dioxide and optimize the resistance against carbonation of GPC.

based geopolymer concrete against higher temperatures. The performance of bonding of geopolymer concrete strengthened with plain steel rebars and ribbed steel rebars was assessed by Zhang et al. 2018b [100]. Figure 14 shows the relationship between the geopolymer concrete specimen's bonding strength and different temperatures. For all specimens, the bonding strength varied marginally when the heat was under 300°C, potentially due to variation in the internal arrangement of GP instigated by higher heat. This tendency of strength is identical to compressive strength and splitting tensile strength of geopolymer concrete. The test outcome specified that 300°C was an essential value for higher variation in the bonding strength of specimens. As shown in Figure 14, the bonding strength of geopolymer concrete with ribbed rebars at room temperature was double that of geopolymer concrete with plain rebars. The deterioration rate of plain rebars was more than ribbed rebars. The bond

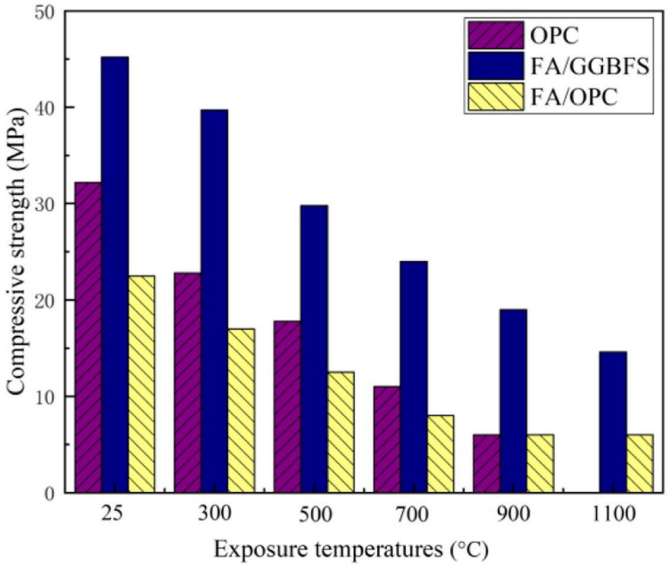


Fig. 13. Compressive strength of samples after heating at different temperatures [91]

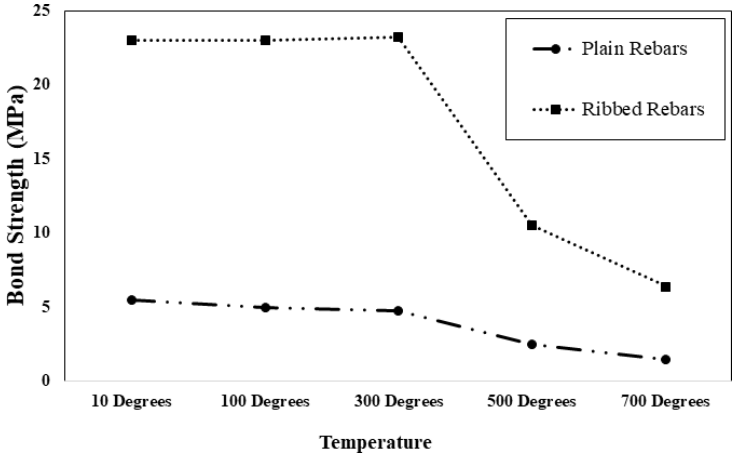


Fig. 14. Bonding strength of FA-based geopolymer concrete with plain and ribbed rebars under different temperatures [102]

strength amid the GP and plain rebars is mostly intricate friction and adhesion. With raise in heat, the geopolymer concrete was harshly degraded, leading to distortion and discordancy amid plain rebars and GPC, which decreased the friction [101]. Hence, the bond mechanism clarifies why the plain rebars showed a reduced pull-out strength than geopolymer concrete with ribbed rebars.

5. Microstructure studies

Myers et al. [103] revealed that geopolymer's microstructure changes with the sort of chemical utilized. The cross-linked arrangement of geopolymer (GP) comes from geo-polymerization. Provis (n.d.) reported the cross-linked replaced model for the gel of calcium-aluminate-silicate-hydrate, which defined the different phases in GP as a blend. In FA-based GPC, the initial product of the reaction is a gel of alkali silico-aluminate comprising silica and alumina unevenly dispersed

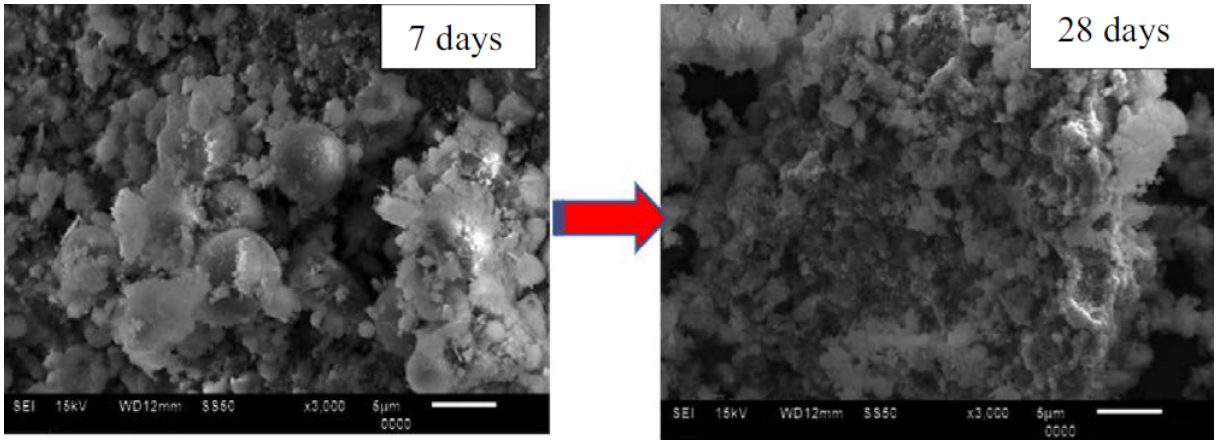


Fig. 15. Change in the microstructure of FA-based GPC with time [107]

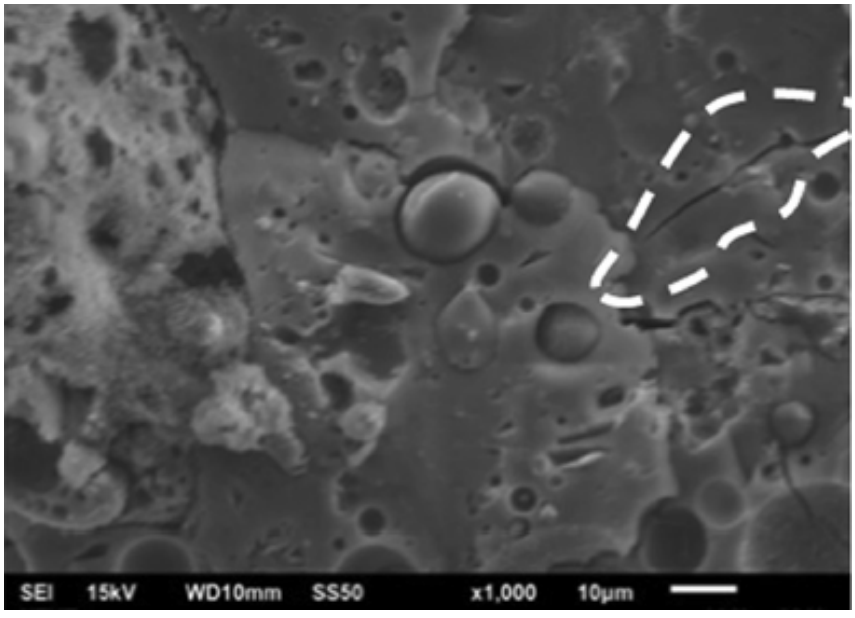
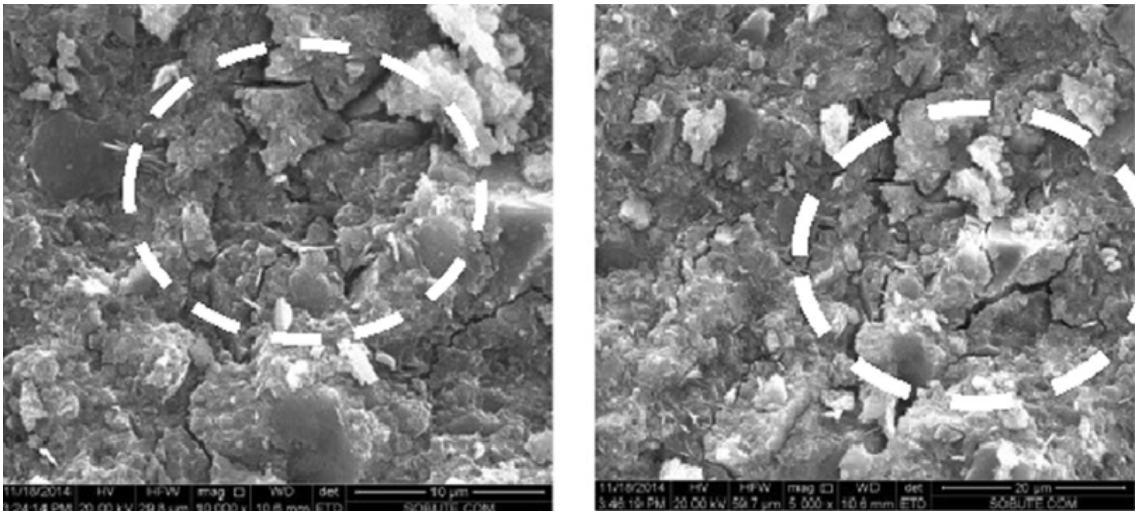


Fig. 16. Micro-cracks in the microstructure of GPC cured in outside surroundings for 6 months [108]

and cross-linked. When sodium hydroxide is utilized as an alkaline solution in GP, the developed gel is called a gel of sodium-aluminate-silicate-hydrate [104]. Moreover, lab tests performed by Garcia-Lodiero et al. [105] Click or tap here to enter text. revealed that without calcium, sodium-aluminate-silicate-hydrate would change into calcium-aluminate-silicate-hydrate at a higher pH level till the accessible calcium is consumed. Bondar et al. (2011) [106] researched the microstructure of sodium-aluminate-silicate-hydrate gel. They revealed that it was a shapeless gel comprising cross-linked alumino-silicate and polymerics identical to calcium-aluminate-silicate-hydrate gel. The shape of fly ash for GPC is rounded. Das et al. [107] researched the development of GPC microstructure containing SiO_2 and CaO substituting fly ash. Different proportions of SiO_2 and CaO were utilized to substitute FA. It was revealed that at 7 days, particles of FA weren't completely reactive due to the early course of geo-polymerization. The microstructure got very dense and packed within 28 days, however, due to the formation of gel of sodium/calcium-aluminate-silicate-hydrate



(A) (B)

Fig. 17. Infiltration of chlorides in FA-based GPC at higher content of water (A) 10000 magnification, (B) 5000 magnifications [109]

within GPC microstructures shown in Figure 15 [107]. The formation of packed GPC microstructure suggests that it could be a durable material and it will last longer against external harmful substances (acids and sulfates). Opposing the above research, some authors [108] noticed micro-cracks in the microstructure of geopolymer concrete comprising FA (see Figure 16) on curing in open surroundings at 6 months in comparison to curing in close surroundings for 6 months. The micro-cracks were due to the reduced compressive strength of GPC. Micro-cracks are very susceptible to external substances, which can lead to the corrosion of steel bars and other harmful activities inside the concrete, ultimately leading to concrete failure. Moreover, the high-water amount in the mixing design in GPC was the reason for the infiltration of chlorides because of the creation of micro-cracks developed by a higher proportion of water (see Figure 17a and 17b) [109].

6. Future possibilities and hurdles for FA-based GPC to be utilized in the construction sector

Research on fly ash–based geopolymer concrete's reaction and fresh properties has become incredibly advanced. Fly ash–based geopolymer concrete is a sustainable material for formation and usage, primarily due to the lower outflow of carbon dioxide and a minor proportion of required water due to the higher amount of fly ash. The conduct of geopolymer concrete is incredible, with no admixture (which is often costly). Furthermore, geopolymer technology offers opportunities for reusing waste materials from industries that couldn't be utilized to form conventional concrete. The previous aspects gratify the social need for sustainable progress. Moreover, fly ash–based geopolymer concrete has wide usage due to its incredible properties, for instance, drying shrinkage, resistance against high temperature, and good resistance against acid, sulfate, and corrosion attack.

Though the above-stated aspects have encouraged the utilization of fly ash–based geopolymer concrete, geopolymer concrete is often being under-utilized in heavy concrete-based construction due to some hurdles, as stated below.

- There are different standards and codes for conventional concrete based on decades of research; the strength equations amid various structural members are based on engineering data and extensive research. Compared to traditional concrete, less research is accessible for fly ash–based geopolymer concrete, regarding complete understanding of its strength and durability behavior under extreme circumstances.
- Though the fly ash–based geopolymer concrete has excellent compressive strength, its strength in tension is still weak, which causes brittle failures. Fibers can be utilized to reinforce the concrete to enhance its ductility and other necessary characteristics.
- Geopolymer concrete can gratify and surpass some of the present performance and standards in construction applications, especially when resistance against acid and temperature is needed. However, the high shrinkage rate can only be optimized by altering the curing situations and utilizing suitable raw ingredients.

7. Economic and Environmental Benefits of FA-based GPC

The development and use of fly ash–based geopolymer concrete provide substantial economic and environmental benefits and contribute to more sustainable construction industry. Economically, adopting industrial waste materials, such as fly ash, in geopolymer concrete production lowers raw material costs and encourages the recycling and repurposing of waste, thereby minimizing landfill requirements and associated expenses. Additionally, the enhanced durability of geopolymer concrete leads to longer service life and reduces the need for frequent repairs or replacements, resulting in long-term cost savings. Environmentally, fly ash–based geopolymer concrete produces significantly lower CO_2 emissions than traditional Portland cement, which is critical in mitigating climate change by reducing greenhouse gas emissions. By utilizing fly ash, a by-product of coal-fired power plants, geopolymer concrete production helps to mitigate the environmental contamination and resource depletion associated with extracting and processing raw materials for conventional cement production. The superior performance of fly ash–based geopolymer concrete in terms of resistance to various environmental conditions, such as acid attacks, freeze-thaw cycles, chloride ingress, and sulfate attacks, further contributes to its environmental benefits by reducing the need for additional protective measures or treatments. This, in turn, lessens the overall environmental footprint of construction projects and conserves natural resources. Moreover, the widespread adoption of fly ash–based geopolymer concrete can stimulate research and innovation in developing sustainable and eco-friendly construction materials. Also, it further promotes the societal shifting towards environmentally responsible practices in the construction sector.

8. Conclusion

The present review study studied and reviewed the reaction mechanism, strength properties, long-term durability under extreme conditions, and microstructural properties of fly ash–based geopolymer concrete; the following conclusion was drawn:

- Predominant raw materials employed in geopolymer concrete production, such as fly ash and slag, are by-products of various industrial processes. Implementing geopolymer concrete can contribute to reducing carbon dioxide emissions, can facilitate the recycling of waste materials, and can promote the advancement of sustainable and eco-friendly practices within society. Consequently, fly ash–based geopolymer concrete is a viable alternative to traditional Portland cement.
- The reaction mechanism in fly ash–based geopolymer concrete involves breaking and reforming silica-oxygen and alumina-oxygen bonds which are triggered by an alkaline chemical solution. This process creates robust geopolymer concrete exhibiting

remarkable strength and durability properties.

- The findings from multiple studies on the resistance of fly ash–based geopolymer concrete to chloride attack have shown considerable variability and inconsistency.
- Fly ash–based geopolymer concrete demonstrates exceptional resistance to sulfate attacks. However, the degradation mechanisms of this material in different sulfate solutions exhibit subtle variations.
- The carbonation mechanism in fly ash–based geopolymer concrete is somewhat influenced by the calcium content in the fly ash. When the calcium-aluminate-silicate-hydrate gel contains higher amounts of calcium, it tends to undergo de-calcification through carbonation.
- Enhancing the degree of polymerization in fly ash and promoting the development of a dense pore structure can effectively improve the resistance of fly ash–based geopolymer concrete to freeze-thaw cycles.

Fly ash–based geopolymer concrete exhibits exceptional resistance to acid attacks, attributed primarily to its dense nanostructure and the abundant presence of calcium/sodium-aluminate-silicate-hydrate gels. These features contribute to the material's ability to withstand harsh acidic environments, making it an advantageous choice for applications where exposure to acidic conditions may be a concern.

9. Recommendations for future studies

The following recommendations are suggested for future research studies based on the present review study:

- Investigate the effects of various types and sources of fly ash on the properties of FA-based GPC to establish guidelines for selecting the most suitable fly ash for specific applications.
- Examine the influence of different alkaline activators, activator concentrations, and curing conditions on the performance of FA-based GPC, aiming to optimize its formulation and processing parameters.
- Conduct long-term field studies to evaluate the real-world performance of FA-based GPC in various structural applications under a diversity of environmental conditions to further validate its potential as a sustainable alternative to conventional concrete.
- Explore incorporating supplementary cementitious materials (SCMs) or fibers to improve the properties of FA-based GPC, such as its mechanical performance, durability, and resistance to environmental degradation.
- Investigate innovative techniques, such as nanotechnology and advanced characterization methods, to better understand the microstructural evolution, reaction mechanism, and material properties of FA-based GPC.
- Assess the life-cycle environmental impacts and economic viability of FA-based GPC compared to conventional concrete, considering factors such as raw material extraction, production, transportation, maintenance, and end-of-life disposal or recycling.
- Develop guidelines, standards, and codes for designing, producing, and applying FA-based GPC in the construction industry to facilitate its widespread adoption and ensure consistent quality and performance.
- Study the potential of FA-based GPC in novel applications, such as 3D-printed construction, prefabricated elements, or specialized infrastructure projects, to further expand its applicability and promote the development of eco-friendly construction technologies.

By addressing these recommendations in future studies, researchers can contribute to the ongoing advancement of FA-based GPC and further

establish its potential as a sustainable and high-performance construction material.

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