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High-performance geopolymer concrete: a review of recent developments

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Abstract: High-performance geopolymer concrete (HPGC) is an advanced construction material designed for enhanced strength, sustainability, and cost-effectiveness. Based on aluminosilicate precursors activated by alkaline solutions, HPGC offers notable advantages over conventional Portland cement concrete. This review synthesizes recent global and Vietnamese studies on HPGC, addressing its constituent materials, mix design, fresh and mechanical properties, durability, environmental impact assessment, microstructure, and potential applications. Industrial by-products such as fly ash, slag, rice husk ash, silica fume, and metakaolin are commonly used in various proportions with alkali activators. HPGC typically shows greater workability, viscosity, and cohesion than traditional concrete. Its compressive strength ranges from 50 to 91 MPa and can exceed 130 MPa under thermal curing, with rapid strength gain supporting faster construction. In terms of durability, HPGC exhibits low permeability and strong resistance to acid, sulfate, and steel corrosion, especially in marine environments. It also offers a significant reduction in carbon emissions compared to conventional concrete. In Vietnam, research on HPGC is still limited but shows promising potential for marine infrastructure applications.

Keywords: High-performance geopolymer concrete, alkali activated materials, fresh properties, mechanical properties, durability, environmental impact assessment.

1. Introduction

Geopolymer concrete is a type of binder system that does not depend on traditional Portland cement. Instead, it is formed through a chemical reaction between an alkaline activator solution and source materials rich in silicon and aluminum. This process, known as geopolymerization, involves the dissolution of aluminosilicate compounds followed by polycondensation into a stable three-dimensional network, as illustrated in Fig. 1. In recent years, geopolymer concrete has attracted increasing attention in the field of construction materials due to its potential as an environmentally friendly alternative to Portland cement. The production of Portland cement is associated with significant carbon dioxide emissions, with approximately one ton of CO_2 released for every ton of cement produced [1]. Globally, the cement industry is estimated to be responsible for nearly 7 percent of total anthropogenic CO_2 emissions [2]. Meanwhile, global demand for cement has continued to grow, rising from 3.7 billion tons in 2014 to 4.7 billion tons in 2020, with an average annual growth rate of around 4 percent [3]. This rising demand not only places additional pressure on the environment but also accelerates the depletion of non-renewable raw materials.

At the same time, a large volume of industrial and agricultural by-products such as fly ash, ground granulated blast furnace slag, silica fume, and rice husk ash remains underutilized despite having high potential as alternative materials. These by-products are rich in reactive silica and alumina and can serve as suitable precursors for geopolymer synthesis [2]. Previous studies have proposed various mix design formulations using these waste materials to produce geopolymer concrete, as shown in Fig. 2. In this context, geopolymer concrete presents a sustainable and technically viable solution by utilizing waste-derived aluminosilicate materials in combination with alkaline activators to produce high-strength construction materials with reduced environmental impact. Recent research has shown that geopolymer concrete can achieve satisfactory compressive strength under ambient curing conditions, and its durability and impermeability can be further improved through the incorporation of supplementary materials such as rice husk ash or metakaolin [4]. Fig. 3 provides a systematic and comprehensive overview of the factors influencing the properties of geopolymer concrete, considering material aspects, environmental conditions, and production techniques. It is highly valuable for mix design and guiding research aimed at improving the performance of geopolymer concrete.

The growing demand for high-performance construction materials is particularly evident in projects that require superior load-bearing capacity and extended service life. In the face of accelerating climate change, modern construction practices must not only adapt to increasingly harsh environmental conditions but also significantly reduce the consumption of natural resources [5]. Consequently, the development of high-performance geopolymer concrete (HPGC) has emerged as a critical area of research. The progressive development stages of HPGC are illustrated in Fig. 4. Future research efforts in this field are expected to concentrate on optimization, comparative performance analysis, and cost-effectiveness evaluation, with the aim of facilitating the application of HPGC in load-intensive, durable, and environmentally sustainable infrastructure. This paper provides a comprehensive overview of the current state of HPGC development both globally and in Vietnam, highlighting existing research gaps and potential directions for further investigation

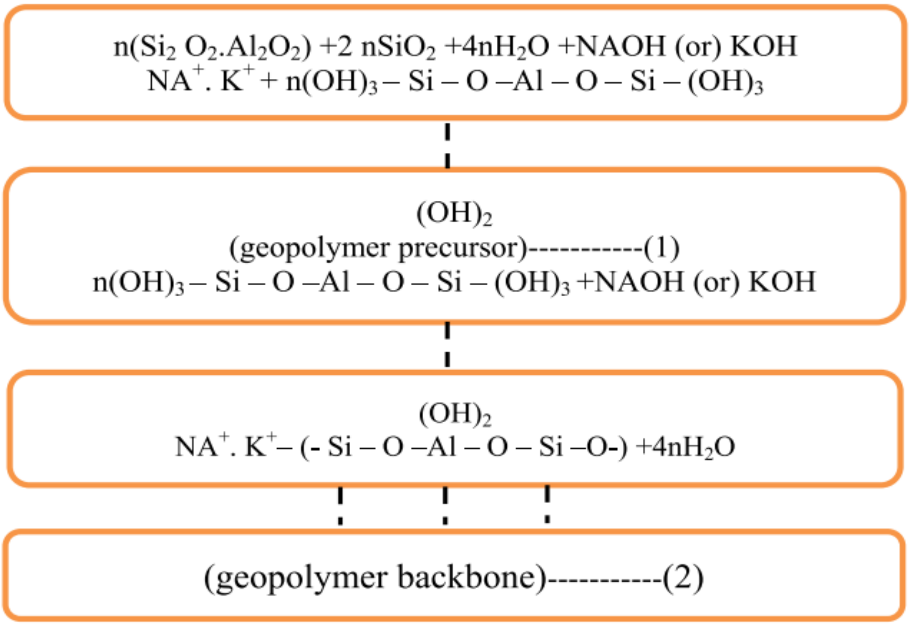

Fig. 1. Geopolymerization reaction [6]

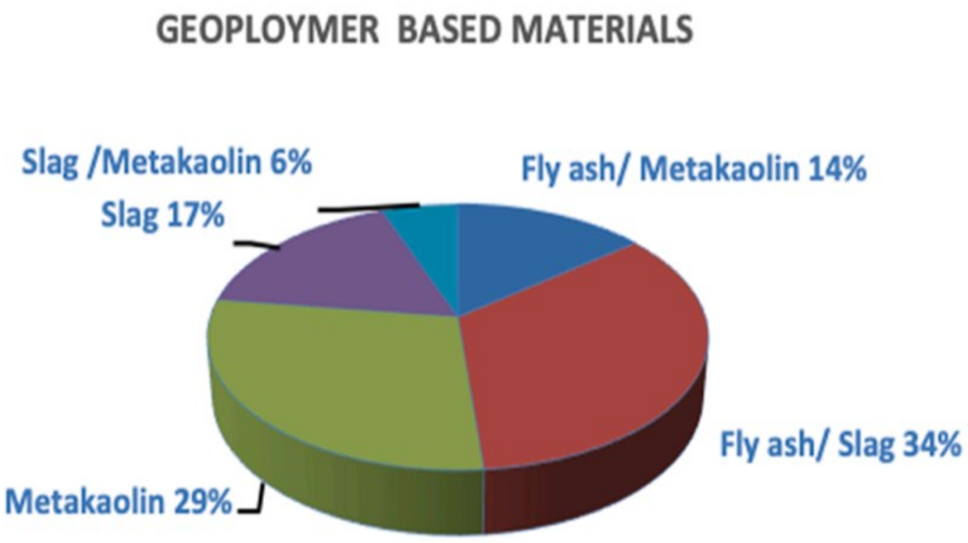

Fig. 2. Geopolymer-based materials [6]

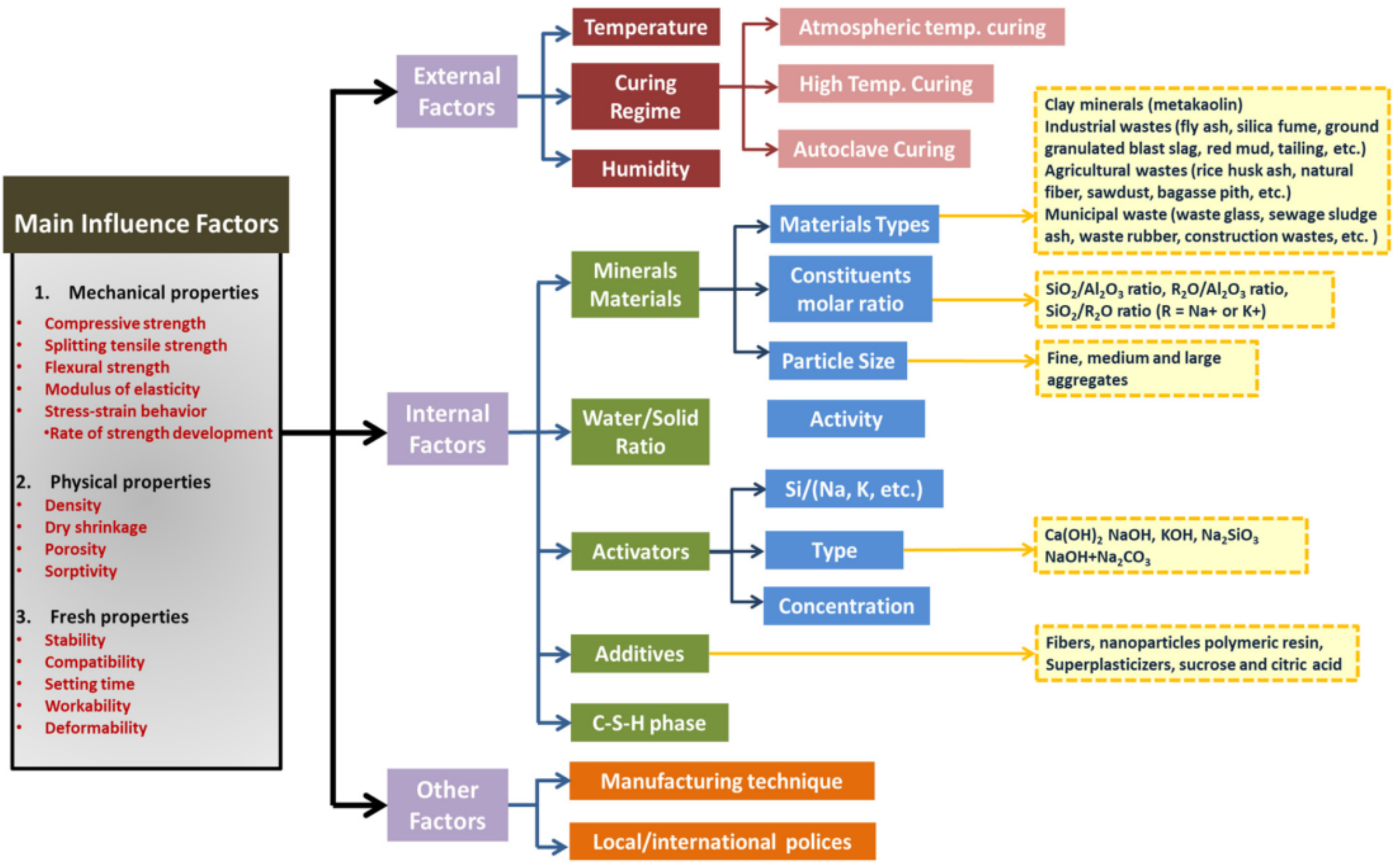

Fig. 3. Key factors influencing Geopolymer Concrete (GeoC) [7]

In recent years, the concept of high-performance geopolymer concrete (HPGC) has attracted increasing attention as researchers attempt to develop geopolymer systems that not only provide high mechanical strength but also enhanced durability and long-term performance. The concept of "high-performance concrete" was originally introduced in conventional Portland cement systems to describe concretes that achieve special combinations of mechanical and durability properties beyond those attainable with conventional mixtures. According to the definition proposed by the American Concrete Institute (ACI), high-performance concrete is characterized by a combination of superior strength, durability, and workability tailored to meet specific service requirements [8, 9]. Following this performance-based concept, high-performance geopolymer concrete in this review is defined as geopolymer concrete designed to achieve both high mechanical strength and improved durability performance compared with conventional geopolymer concrete. In many reported studies, HPGC typically exhibits compressive strengths exceeding approximately 60 MPa while simultaneously demonstrating enhanced resistance to aggressive environments such as chloride ingress, sulfate attack, acid exposure, and elevated temperatures. It should be noted that HPGC is conceptually different from high-strength geopolymer concrete (HSGC), which refers primarily to geopolymer mixtures characterized by high compressive strength alone. In contrast, HPGC emphasizes a broader combination of performance attributes, including strength, durability, and microstructural optimization. Therefore, in this review the term HPGC is used in a performance-oriented sense, consistent with the broader concept of high-performance concrete discussed in previous studies [8-10]. In this review, studies that report compressive strengths below this range are discussed primarily to illustrate the technological progression from conventional geopolymer concrete toward high-performance systems.

This review is based on the Scopus database as the primary search tool for methodology. Keywords such as "geopolymer concrete", "high-performance geopolymer concrete", "high-strength geopolymer concrete", "alkali-activated materials", "mechanical properties", "durability", and "environmental impact" were used. Initially, the search with "geopolymer concrete" returned 4767 results. The scope was then refined by focusing on "high-performance geopolymer concrete" and limiting the time frame to 2020 to 2025, reducing the number of documents to approximately 300, including scientific papers, conference reports, reviews, PhD thesis, and some books or book chapters. Finally, 95 articles were selected for the study. Fig. 5 shows the network of relevant authors cited in studies from 2018 to 2025. The most cited journals include Construction and Building Materials, Journal of Materials in Civil Engineering, Cement and Concrete Research, Journal of Building Engineering, Resources, Conservation & Recycling, Materials, Polymers, and others, sourced from platforms like ScienceDirect (Elsevier), SpringerLink, MDPI,…

2. Raw materials for HPGC

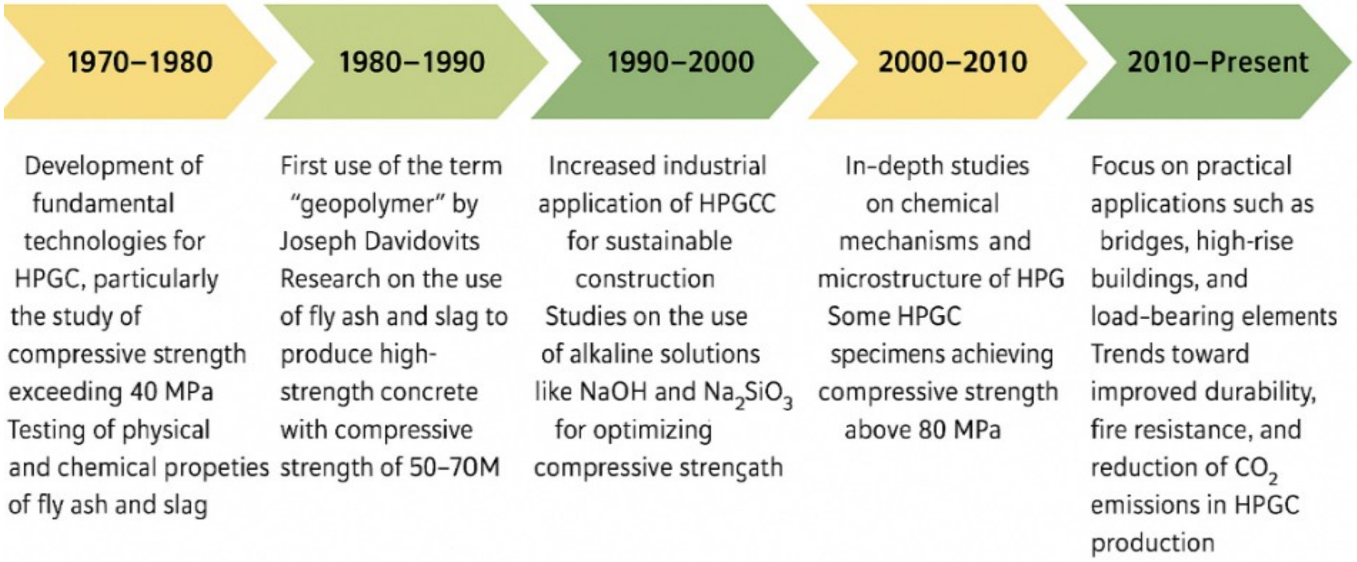

Fig. 4. Development stages of HPGC [11]

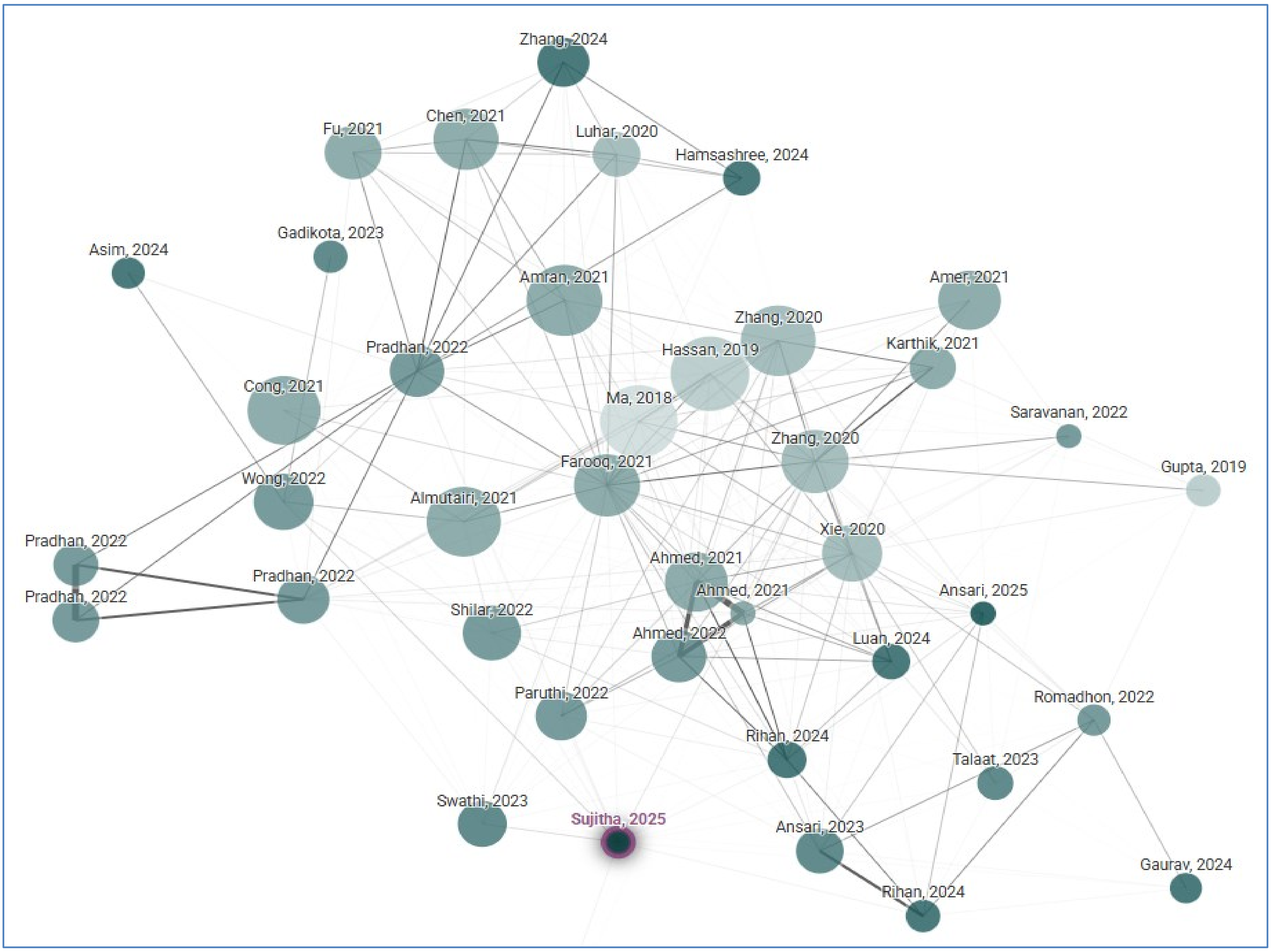

Fig. 5. The network of relevant authors cited in HPGC studies from 2018 to 2025 (Source: https://www.connectedpapers.com)

The main materials used to produce high-performance geopolymer concrete include aluminosilicate-based precursors for the geopolymerization reaction, an alkaline activator solution, coarse aggregates (such as gravel or crushed stone), fine aggregates (such as sand), water, and chemical admixtures.

Geopolymers and calcium-rich alkali-activated materials (AAMs) are often grouped under the broader category of alkali-activated binders; however, the two systems differ markedly in their gel structures and reaction mechanisms. In the classical definition by Davidovits [12], geopolymers are produced from low-calcium aluminosilicate precursors, forming a poly(sialate) network and a characteristic N–A–S–H gel through dissolution and polycondensation processes. In contrast, calcium-rich systems are classified by the RILEM TC 224-AAM [13] report as AAMs, where the primary reaction product is C-(N)-A-S-H gel, which resembles the C–S–H gel found in Portland cement. The precipitation-dominated reactions in these systems, together with the strong influence of calcium content, lead to notable differences in setting behavior, early-age strength, and long-term durability. In this review, the term “geopolymer” is used specifically for low-calcium systems that form N–A–S–H gels, while FA/GGBFS-based high-calcium binders are categorized as AAMs. This distinction ensures consistency when interpreting mechanical performance, microstructural development, and durability characteristics across different material classes.

2.1. Aluminosilicate-based precursor

All raw materials containing silicon and aluminum oxides in an amorphous phase can serve as effective precursors for geopolymer synthesis. Common examples include kaolinitic clay, metakaolin, fly ash, ground granulated blast furnace slag (GGBFS), as well as blended systems such as fly ash–slag and fly ash–metakaolin mixtures. Among these, thermally activated materials—particularly metakaolin, fly ash, and slag—are generally preferred for the production of high-performance geopolymer concrete (HPGC), as they exhibit higher reactivity compared to uncalcined or naturally occurring aluminosilicate sources such as raw clay, kaolin, or other silicoaluminate minerals. Furthermore, amorphous phases dissolve more readily in alkaline environments than their crystalline counterparts, thereby promoting faster geopolymerization kinetics [14].

Fly ash (FA) is among the most commonly used precursor materials in geopolymer research and practice, owing to its favorable physical properties and cost-efficiency. It contains reactive aluminosilicate phases in the form of fine spherical particles, typically ranging from 0.5 to 100 μm, which enhance the dissolution rate and the subsequent polymerization process. Fly ash is also significantly less expensive than metakaolin or slag and is abundantly available, particularly in regions with well-developed coal-fired power infrastructure. However, recent studies have shown that high-calcium fly ash (Class C, ASTM) tends to promote the formation of hybrid C–A–S–H gels, which alter the chemical stoichiometry and interfere with the geopolymerization mechanism, thereby reducing acid resistance — one of the hallmark advantages of HPGC. In contrast, low-calcium fly ash (Class F, ASTM) predominantly forms stable N–A–S–H gels, resulting in a more durable and chemically stable aluminosilicate network [15].

Ground Granulated Blast Furnace Slag (GGBFS), a by-product of the steel manufacturing process, has been extensively utilized—either individually or in combination with fly ash—for the synthesis of geopolymer concrete, as demonstrated in both domestic and international studies. One of the key advantages of GGBFS is its ability to react with calcium-rich components under ambient curing conditions, enabling the production of geopolymer concrete without the need for elevated temperature curing. However, its application also presents challenges, including compositional variability, non-uniform particle sizes, and the additional energy required for fine grinding, all of which contribute to higher production costs. In Vietnam, GGBFS is commercially available in ground form and is widely adopted in experimental and applied research on geopolymer concrete [16].

Metakaolin (MK) is produced by calcining kaolinitic clay at approximately 700 °C for 24 hours. While this process significantly increases production costs due to its energy-intensive nature, it results in a highly reactive material. The thermal treatment disrupts the original crystalline structure, enhancing MK's reactivity with alkaline activators and facilitating the formation of geopolymeric gels. However, the platy morphology of MK particles leads to higher water demand relative to other aluminosilicate precursors, which can increase the porosity of the hardened binder matrix. This, in turn, may reduce the mechanical strength and durability of the final product. These limitations have contributed to the relatively limited use of metakaolin in both national and international studies on geopolymer materials. Recent density functional theory (DFT) simulations (Wan et al., [17]) have demonstrated that when the Si/Al ratio exceeds 2, the geopolymer structure tends to develop a denser three-dimensional network. This structural configuration accounts for the high chemical reactivity observed in metakaolin-based systems, while also revealing an inherent tendency toward the formation of micro-porosity within the gel matrix.

Naturally occurring minerals rich in aluminum and silicon can also be employed as precursors for geopolymer synthesis. Additionally, supplementary materials such as rice husk ash and silica fume are sometimes incorporated into the mix design to enhance specific properties of high-performance geopolymer concrete.

2.2. Alkaline activators

2.2.1. Liquid Alkaline activators

Strong alkaline solutions are commonly used as activators in the synthesis of geopolymer materials. Among these, sodium hydroxide (NaOH) or potassium hydroxide (KOH) combined with sodium silicate (Na_2SiO_3) or potassium silicate (K_2SiO_3) are the most prevalent. Experimental results indicate that geopolymer concrete (GPC) activated with NaOH typically achieves higher compressive strength, followed by those activated with Na_2SiO_3. A higher Na_2O content in the activator generally enhances compressive strength. Furthermore, Palomo et al. [18] demonstrated that alkaline solutions containing soluble silica—such as Na_2SiO_3 or K_2SiO_3—promote a significantly higher rate of geopolymerization than hydroxide-only activators. This is attributed to the presence of dissolved silica, which increases the paste density but can also reduce workability. Similarly, Xie et al. [19] reported that increasing both the dosage and molarity of the alkaline activator positively influences the compressive strength of geopolymer concrete.

L. Gautam [15] successfully produced high-performance geopolymer concrete (HPGC) with compressive strengths up to 70 MPa using low-concentration NaOH solutions (3M–6M) and fly ash as the primary precursor, under ambient curing conditions. Nagarajan Arunachalam et al. [20] achieved a compressive strength of 79 MPa using a combination of Na_2SiO_3 and NaOH (2.5:1 ratio), along with 2% microsilica and copper slag, cured under steam conditions. M. Rao et al. [21] developed an HPGC mixture incorporating 35% fly ash, 50% ground granulated blast furnace slag (GGBFS), and 15% silica fume as the binder, activated by a NaOH–Na_2SiO_3 system and cured at room temperature. The addition of copper-coated steel fibers and the use of a high-range water-reducing admixture significantly enhanced workability and mechanical performance, resulting in a 28-day compressive strength of 91.36 MPa. In a subsequent study, M. Liu et al. [22] proposed an optimized mixture comprising 15% fly ash and 10.3% silica fume, with a Na_2SiO_3/NaOH ratio of 2.5 and a NaOH concentration of 10 M. The specimens were subjected to hot water curing at 80 °C for 24 hours.

2.2.2. Solid/dry Alkaline activators

In Vietnam, Dang Thuy Chi [14], introduced a dry powder activator primarily consisting of crystalline sodium silicate, which was dry-blended with fly ash and slag. This approach simplified the mixing process, improved safety, and eliminated the need for thermal curing. More recently, Dinh Hoang Quan [23] proposed a modified solid activator system comprising $Na_2SiO_3 \cdot 5H_2O$ and Na_2CO_3, replacing conventional liquid activators (Na_2SiO_3 + NaOH). This formulation extended the initial and final setting times to 100 and 205 minutes, respectively, and yielded a 28-day compressive strength of 57.48 MPa, demonstrating its potential for practical applications in ambient-cured HPGC.

2.2.3. Alkaline activators selection guidance

The selection of activators should be determined based on the performance requirements and construction conditions of each type of geopolymer concrete. For high-performance geopolymer concrete (HPGC) with a compressive strength of 60–90 MPa, a liquid activator system comprising NaOH (6–10 M) combined with Na_2SiO_3 at a Na_2SiO_3/NaOH ratio of approximately 2.5:1 has been found effective. The incorporation of micro-silica or silica fume enhances matrix densification, while superplasticizers are essential to maintain workability. Although heat curing can accelerate strength development, an optimized mix can still achieve satisfactory performance under ambient conditions. For in-situ applications or cases without heat curing, solid activator systems such as crystalline Na_2SiO_3 or $Na_2SiO_3{\cdot}5H_2O$ combined with Na_2CO_3 offer a safer and more practical alternative, albeit typically yielding lower strength. In specialized applications, such as acid-resistant or marine-exposed geopolymer concretes, activator systems with a high content of soluble silica are recommended to promote geopolymerization and enhance chemical durability [14], [23].

2.3. Aggregates and chemical admixtures for HPGC

High-performance geopolymer concrete (HPGC) typically utilizes river sand and crushed stone as fine and coarse aggregates, respectively, in a manner similar to conventional Portland cement concrete. However, D. Dao and S. Trinh [24] investigated the complete substitution of natural aggregates with steel slag and reported encouraging results regarding both mechanical performance and sustainability. Rao et al. [21] highlighted the use of superplasticizers such as Auramix 300 to improve the workability of the fresh geopolymer mixture by reducing internal cohesiveness and viscosity, thereby facilitating easier mixing and placement. Among the available superplasticizer types, those based on naphthalene sulfonate have been found to be more effective than their polycarboxylate counterparts in the context of HPGC. Furthermore, set-retarding admixtures have been employed to regulate setting time and mitigate rapid slump loss, which is beneficial for maintaining workability during extended construction periods. Copper-coated steel fibers have also been incorporated into HPGC formulations to enhance key mechanical properties, including tensile and flexural strength [16].

The proportions of precursor materials, the concentration and ratio of the alkaline activator solution, and the water-to-binder ratio are all critical parameters that significantly affect the fresh-state behavior as well as the mechanical and physical properties of HPGC.

3. Mix design methods for HPGC

In recent years, research on geopolymer concrete (GPC) has advanced considerably, with several countries introducing technical standards and guidelines for its practical application. For example, RSN 33684 from Ukraine provides instructions for producing binders derived from blast furnace slag; PAS 8820 from the United Kingdom outlines technical requirements and performance evaluation criteria for geopolymer concrete; and GB/T 29423 from China specifies standards for corrosion resistant geopolymer concrete, including definitions, classification, raw material requirements, technical specifications, and testing methods. Despite these developments, the widespread adoption of GPC remains hindered by the absence of standardized procedures and comprehensive mix design guidelines, particularly in contexts where material sources and service conditions vary. In Vietnam, the development of national standards or technical guidelines for the mix design of GPC is still in progress [16].

Globally, several mix design approaches for GPC have been proposed, though each exhibits certain limitations. Rangan et al. [25] introduced a pioneering method utilizing one hundred percent fly ash; however, this approach did not consider the specific gravities of constituent materials. Ramachandran et al. [26] proposed a methodology based on Indian standards, replacing the traditional water to binder ratio with an alkaline solution to binder ratio, though the results were still unsatisfactory. Reddy et al. [27] developed empirical charts relating the alkaline solution to binder ratio to compressive strength, but the method relied on fixed input parameters, limiting its adaptability. Li et al. [28] applied particle packing theory and the Taguchi method, yet the broad range of input variables and minimal use of fly ash resulted in higher costs. Overall, these methods have yet to comprehensively address the combined effects of key factors influencing both the strength and workability of geopolymer concrete.

A variety of mix design strategies have been explored for high performance geopolymer concrete. The trial and error method remains commonly employed, as demonstrated in studies by Hardjito [29] and Davidovits [30], to empirically optimize mixture compositions. Response surface methodology was applied by Gulati [31] and Sadiq [32] to optimize the ratio of sodium silicate to sodium hydroxide and the molarity of sodium hydroxide. Particle packing optimization, as used by Provis and van Deventer [3], was intended to achieve maximum density within the mix. Cheng [33] and Patankar [34] employed a water to binder ratio approach to balance workability and compressive strength. Multi objective optimization algorithms were investigated by Romagnoli [35] to determine optimal mix proportions. Furthermore, numerical tools such as Design Expert and MATLAB have been utilized, as reported by Mohabbi [36], to enhance the efficiency and precision of GPC mix design processes.

According to Gautam [15], no standardized mix design methodology for high performance geopolymer concrete has been established thus far, owing to its classification as a novel material. As a result, mix proportions are typically developed through experimental procedures based on target strength and workability requirements. In this context, M. Liu et al. [22] applied response surface methodology to model and optimize the relationship between input parameters and response variables. This technique is widely adopted in concrete mixture design. Their study employed the response surface central composite design method to optimize the mix proportions of high strength geopolymer concrete, considering four main factors: fly ash content (A), silica fume content (B), the ratio of sodium silicate to sodium hydroxide (C), and the molarity of sodium hydroxide (D). The performance indicators were compressive strength and split tensile strength. The experimental matrix consisted of thirty runs, including twenty four factorial points and six center points. The mix proportions of the reference HPGC are presented in Table 1.

Several studies have also addressed the mix design of high-performance (HPGC) and ultra-high-performance geopolymer concrete (UHPGC), taking into account the Si/Al ratio, the activator modulus (Ms), and curing conditions. Li et al. [37] proposed a performance-based mix design guideline for geopolymer concrete using a combination of ground granulated blast furnace slag (GGBFS) and fly ash, activated by a mixed alkaline solution of Na_2SiO_3, Na_2CO_3, and NaOH. Their approach was founded on the theories of aggregate packing density, excess paste thickness, and the Taguchi optimization method. The investigated parameters included N/CKD (0.5–0.35), representing the water-to-binder ratio; TB/CKD (0–45%), the fly ash-to-binder ratio; tpaste (32–56 μm), the excess paste thickness surrounding aggregates; Na/CKD (4–7%), the Na_2O content in the activator relative to the binder; and Ms (0.5–2), the activator modulus defined as the SiO_2/Na_2O ratio in the alkaline solution. Although this study comprehensively considered the major factors influencing HPGC performance, its practical application remains limited due to several challenges: the selection ranges for Na/CKD and N/CKD were excessively broad; the relatively low fly ash content (20–40%) increased production costs and reduced environmental benefits; there was no specific guidance for optimizing the technical and economic balance between N/CKD and Na/CKD; and determining tpaste and aggregate surface area introduced further complexity in practical implementation.

According to Xu et al. [38], a preliminary mix design method for UHPGC was proposed for civil engineering applications. The study employed aluminosilicate-rich precursors, including ground granulated blast furnace slag (GGBFS), rice husk ash (RHA), silica fume (SF), and fly ash (FA), activated by an alkaline solution composed of NaOH and Na_2SiO_3. The mix design was developed based on the target strength approach, in which the relationship between compressive strength, water-to-binder ratio (w/b), and Na_2O content was analyzed, as illustrated in Fig. 6. Compared with the findings of Li et al. [39], the composition of each constituent material was determined through the molar ratios of their respective oxides, providing a more precise understanding of the contribution of each phase to the overall properties of the composite (Fig.7). Nevertheless, further efforts are required to establish standardized mix design guidelines to enhance the practical implementation of this type of concrete.

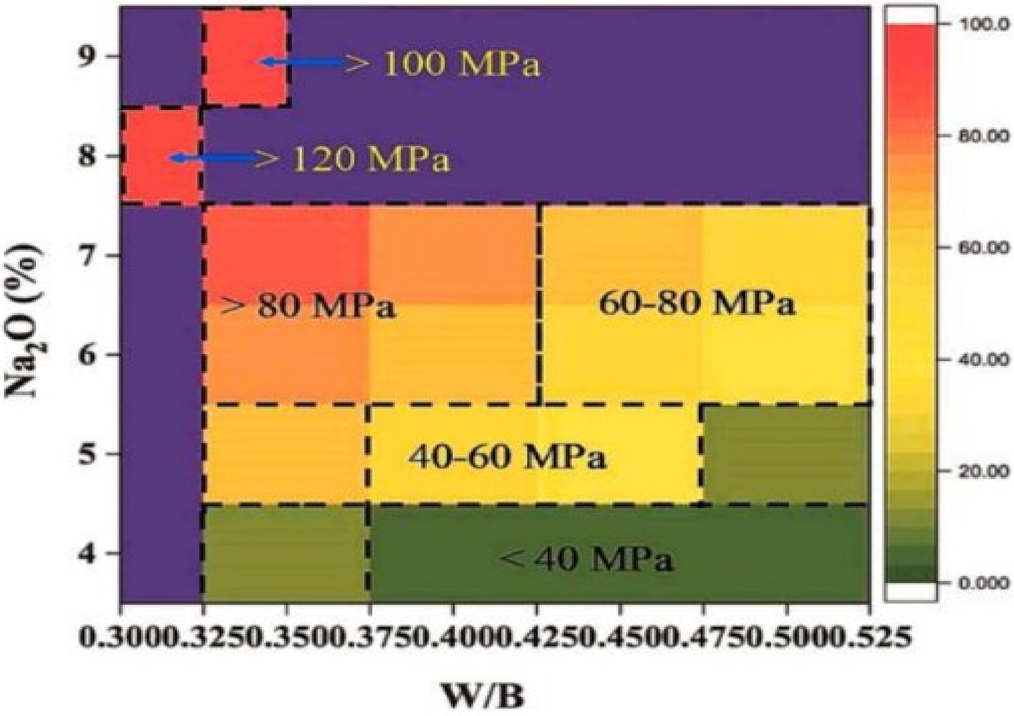

Fig. 6. Compressive strength of geopolymer concrete in relation to the water-to-binder ratio (W/B) and Na_2O content [38].

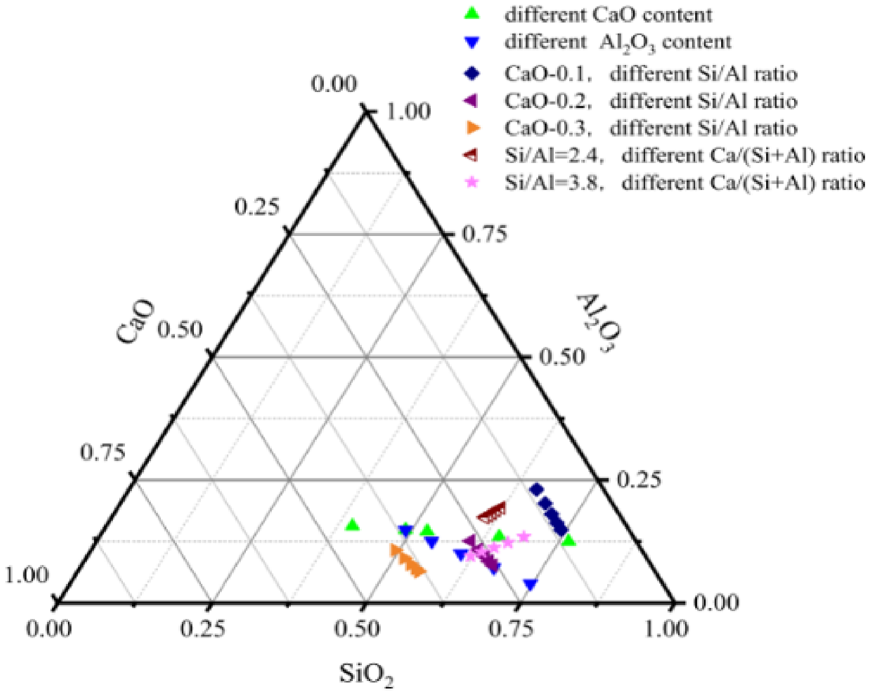

Fig. 7. The designed oxide molar composition of the solid precursors [39]

The preparation process for high strength geopolymer concrete involved the following steps: Sodium hydroxide solutions with molarities of ten, twelve, and fourteen molar were prepared and mixed with sodium silicate to form the alkaline activator, which was then allowed to cool. Ground granulated blast furnace slag, fly ash, and silica fume were dry mixed for two minutes, followed by the addition of manufactured sand and an additional one minute mix. The alkaline activator and a set retarder diluted in water were then added, and the entire mixture was stirred for another two minutes. The fresh concrete was poured into molds and vibrated for two minutes to eliminate air voids. Specimens were initially cured at ambient temperature for twenty four hours before being demolded and subsequently cured in a hot water bath at eighty degrees Celsius for another twenty four hours. The detailed preparation procedure is illustrated in Fig. 8.

Several studies in Vietnam, including those by Tran Viet Hung [40], Pham Quang Dao [41], and Dang Thuy Chi [14], have employed Rangan's method for the mix design of fly ash-based geopolymer concrete, integrated with experimental design approaches. Dinh Hoang Quan [23] proposed a mix design methodology based on the development of an artificial neural network and a mathematical model to predict slump and 28-day compressive strength.

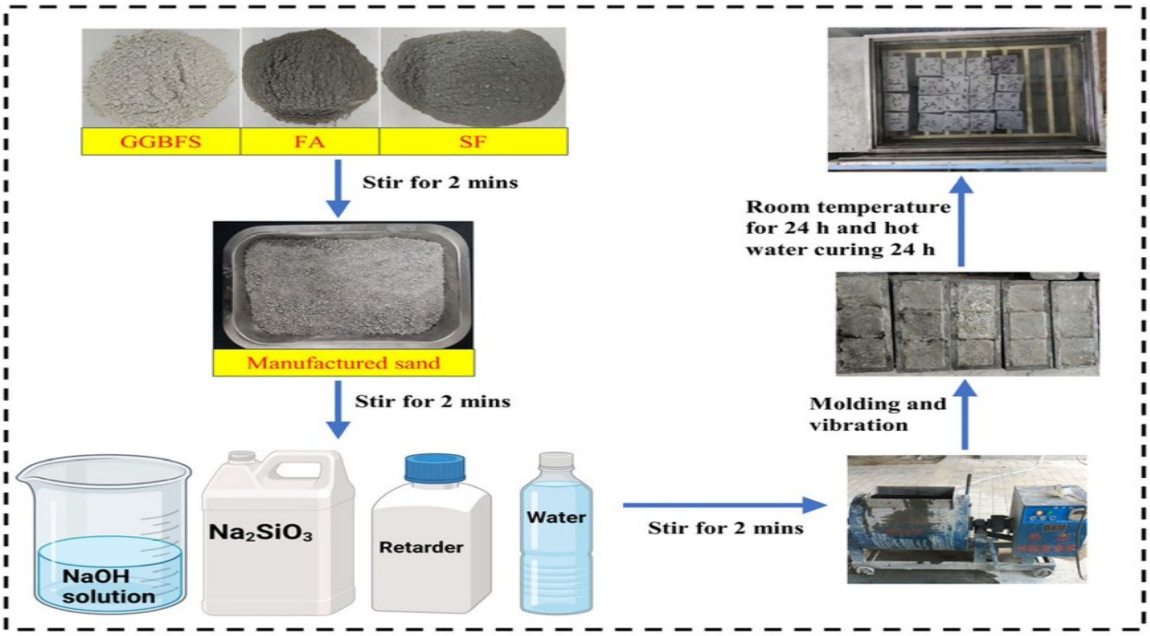

Fig. 8. Preparation process of HPGC specimens [22]

Table 1. Mix Design Results of HPGC, OPC

Author	Type of concrete	Cement (kg/m³)	FA (kg/m³)	GGBFS (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	Alkaline activator (kg/m³)	W/B ratio	Chemical admixture (kg/m³)	28-day Compressive Strength (MPa)	Curing
L. Gautam (2015) [15]	HPGC	0	50	300	805	900	285	0.59	0	71.85	Ambient condition
	OPC	394	0	0	789.11	1097.25	0	0.40	7.88	70.80	Ambient condition

4. Fresh properties of HPGC

Fresh concrete refers to the condition of concrete immediately after mixing, before the onset of setting or hardening. High-performance geopolymer concrete (HPGC) typically exhibits high viscosity and good workability, which can be tailored by adjusting the water content and superplasticizer dosage. Owing to the nature of alkaline activation, HPGC generally sets faster than conventional concrete and shows reduced bleeding when a low water-to-binder ratio is used [42]. Kamal Neupane et al. [8] developed two types of high performance geopolymer concrete (HPGC), namely the GP mixture consisting of 70 percent fly ash and 30 percent slag, and the HF mixture containing 40 percent fly ash and 60 percent slag. Both were cured under ambient conditions. In terms of workability, the HPGC mixtures exhibited flowability comparable to that of ordinary Portland cement (OPC) concrete, despite containing approximately 30 percent less water and without the use of any chemical admixtures. In contrast, the OPC control mix incorporated a high range water reducing admixture, suggesting that under equivalent water content, the HPGC mixture would likely demonstrate even higher slump values. Fig. 9 presents the slump loss behavior of the different concrete mixtures over a two hour period. At a compressive strength grade of 65 MPa, the HPGC mixture showed a lower rate of slump loss compared to the OPC mix. For the 80 MPa grade, both mixtures exhibited similar slump retention characteristics. Unlike OPC concrete, the setting time of HPGC cannot be effectively extended using conventional commercial admixtures. This limitation is likely attributed to the distinct chemical composition of the geopolymer system, particularly its high alkalinity relative to that of Portland cement. This presents a major challenge for the commercial application of HPGC. Moreover, fresh HPGC tends to exhibit higher viscosity and stickiness, along with a greater tendency for air entrapment, which makes the mixing and casting process more difficult. Therefore, further research is needed to develop appropriate chemical admixtures to improve the cohesion and workability of fresh HPGC.

A recent study by Amer et al. [43] reported that the workability of geopolymer concrete, including high performance geopolymer concrete (HPGC), can be improved by incorporating 2% naphthalene sulfonate based superplasticizer (NS). In contrast, the use of a polycarboxylate based superplasticizer (PC) had minimal effect. The mix containing NS achieved the highest initial slump of 200 mm and exhibited the lowest slump loss, with a reduction of 110 mm after 15 minutes and 145 mm after 20 minutes. Meanwhile, the PC mix showed a lower initial slump of 120 mm and a rapid loss of workability, with a reduction of 110 mm after 15 minutes and complete loss of workability after 20 minutes.

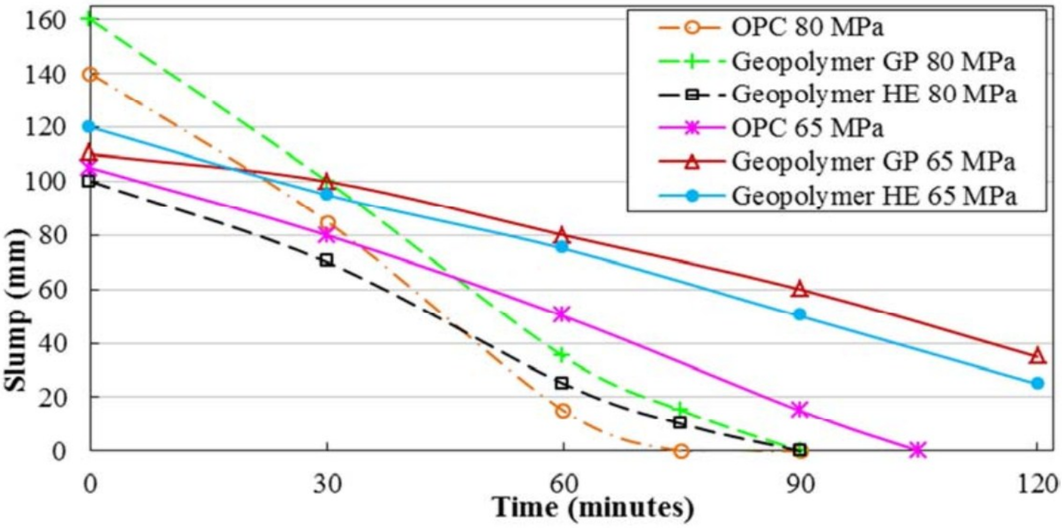

Fig. 9. Slump loss over time of HPGC [11]

In a study by M. Sherif et al. [6], the workability of high strength concrete (HSC) and high strength geopolymer concrete (HSGC) was compared using various supplementary cementitious materials, including fly ash, ground granulated blast furnace slag, and metakaolin. For the HSC control mixtures, the CEM I 500 sample recorded the lowest slump value of 135 millimeters. This value increased with partial replacement of cement by 10 percent metakaolin, followed by an increase with 10 percent fly ash (reaching 155 millimeters), and peaked at 165 millimeters, equivalent to a 22 percent increase, when 10 percent ground granulated slag was used. Within the HSGC mixtures as illustrated in Fig. 10, increasing the slag content led to higher slump values, indicating better homogeneity. In contrast, a higher content of metakaolin resulted in a reduction in slump, as also reported in reference.

Although HSGC is characterized by high viscosity, it maintains good workability due to the presence of fine particles with spherical geometry, smooth surfaces, and hollow structures. The addition of superplasticizers significantly enhances the workability. It is noteworthy that geopolymer concrete made entirely with slag exhibited lower slump compared to mixtures in which slag was partially replaced with metakaolin. An increase in metakaolin content improved the flowability, highlighting the importance of particle size and morphology in determining the rheological behavior of the material. The current use of slag and metakaolin particles with different sizes is an effective strategy to improve the flow characteristics of HPGC mixtures. In general, the workability of HPGC is primarily influenced by the chemical composition of the raw materials and the curing temperature [6].

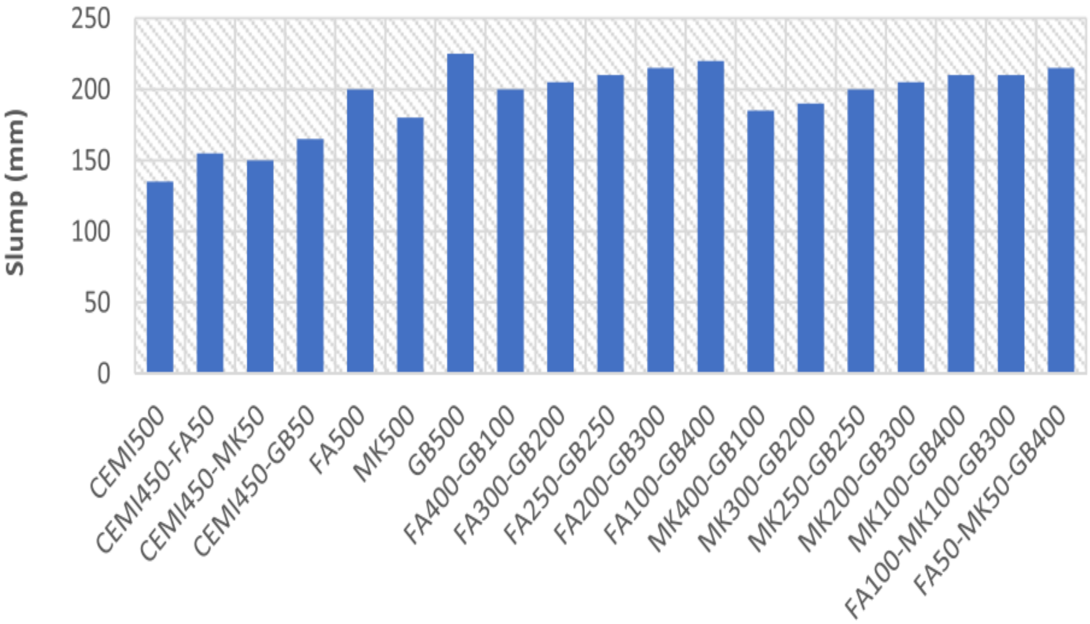

Fig. 10. Flowability of HSC and HSGC [6]

[Caption for the symbols in Fig. 10: The horizontal axis of the graph represents the mix design codes corresponding to each concrete specimen (a total of 19 samples). Each code denotes a different mix composition of high-performance geopolymer concrete (HPGC), reflecting variations in the proportions of cement (CEMI), fly ash (FA), metakaolin (MK), and ground granulated blast furnace slag (GGBFS) used in the mixtures. The accompanying numerical values indicate the mass (in kilograms) of each constituent material incorporated in the mix]

In Vietnam, Le Thanh Ha [44] investigated the influence of superplasticizers on the properties of geopolymer mortar. The study found that the use of high range water reducing admixtures, specifically Sika ViscoCrete 3000 20M and Sika ViscoCrete 8565, significantly improved the workability of both geopolymer and Portland cement mortars. However, the improvement was more pronounced in the cement based mortars compared to the geopolymer mortars. The influence of the two admixtures on the workability of both mortar types was found to be generally similar.

5. Structural characterization of HPGC

5.1. Microstructure of High-performance geopolymer concrete

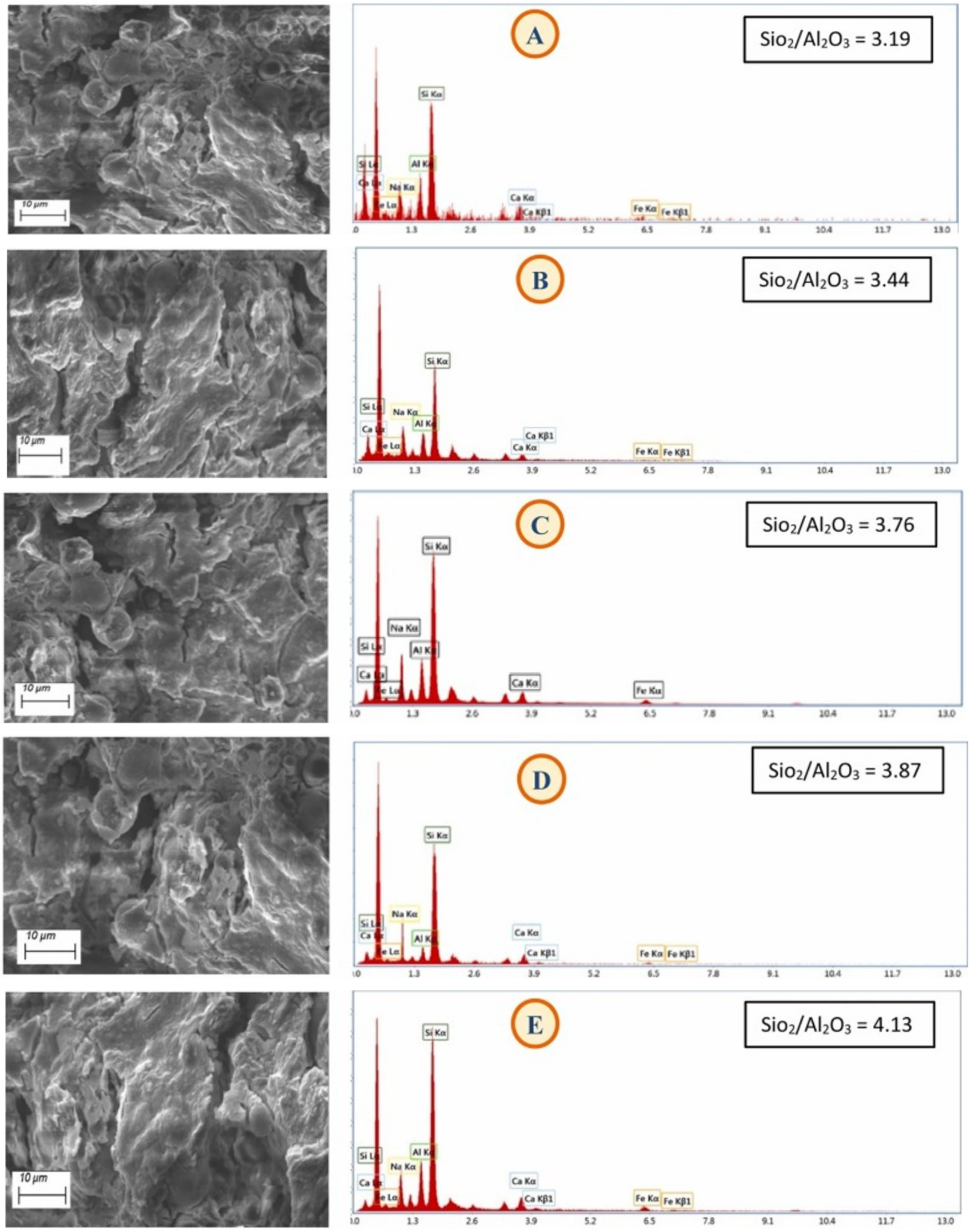

Fig. 11. EDX and SEM analysis for tested mixes (A) Control ↱(B) 1S+ 1 A ↱(C) 1S/1A-6 ↱(D) 1S/1A-8 (E) 2 S/1A-6 [45]

According to Arab et al. [45] SEM-EDX analysis was used to evaluate the microstructure of HPGC containing nanomaterials. The primary aim was to determine the density and SiO_2/Al_2O_3 ratio in the geopolymer matrix, crucial factors influencing the mechanical and physical properties of the material, EDX results identified Si, Al, and Na as the main elements. Increasing the nanosilica and nanoalumina content raised the SiO_2/Al_2O_3 ratio and improved the geopolymerization process.

The control sample achieved a compressive strength of 61.97 MPa with a dense microstructure. In contrast, the 1S+1A, 1S/1A-6, and 1S/1A-8 samples had SiO_2/Al_2O_3 ratios of 3.44, 3.76, and 3.87, respectively, with a uniformly developed geopolymer matrix (Fig. 11). SEM images showed a marked reduction in porosity and an increase in structural density with higher nanomaterial content, especially nanosilica. The simultaneous addition of nanosilica and nanoalumina—via physical mixing and thermal activation—resulted in a denser, more homogeneous microstructure compared to the control sample. Overall, nanomaterial incorporation significantly improved particle bonding, reduced porosity, and enhanced both mechanical strength and long-term durability of geopolymer concrete.

Nagarajan Arunachelam et al. [20] studied the microstructure of high-strength geopolymer concrete (HGPC) incorporating various slags and silica fume using SEM under two curing conditions: ambient and steam. Under ambient curing, due to insufficient heat and water evaporation, the sample contained unreacted fly ash, porosity, and microcracks, slowing down the polymer gel formation and reducing strength. HGPC consisted of three main phases: binder, aggregate, and the interfacial transition zone (ITZ). The reaction between slag and the alkaline solution formed a cementitious gel around the aggregates, improving bonding at the ITZ. However, the ambient-cured sample still contained unreacted fly ash, while the steam-cured sample exhibited a denser structure with nearly complete matrix reaction. SEM and EDS confirmed the formation of N-A-S-H gel (sodium aluminosilicate) containing Na, Si, Al, and O, the key components contributing to HGPC strength (Fig. 12, Fig. 13).

Thus, the combination of SEM and XRD provides a comprehensive understanding of the microstructure and mineral phases of HPGC, clarifying the material formation mechanism and aiding in optimizing the mix design and manufacturing process to improve performance and durability.

5.2. Multiscale correlation between microstructure, mesostructure, and macroscopic properties of HPGC

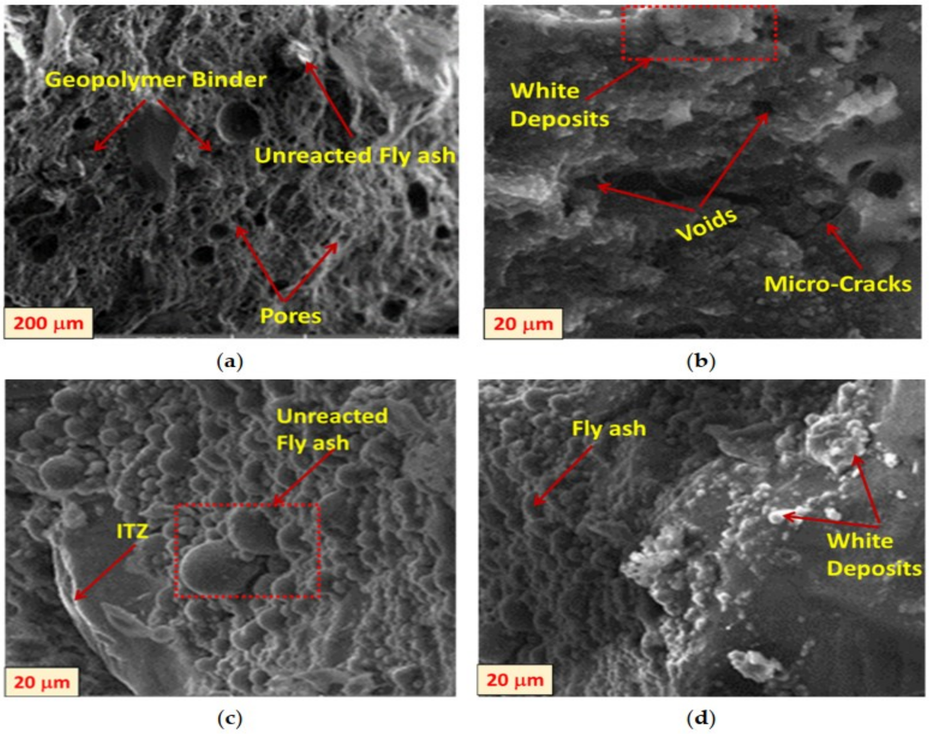

Fig. 12. SEM analysis of ambient-cured HSGPC specimens: (a) presence of pores; (b) presence of voids and microcracks; (c) presence of unreacted fly ash regions; and (d) presence of white deposits [20]

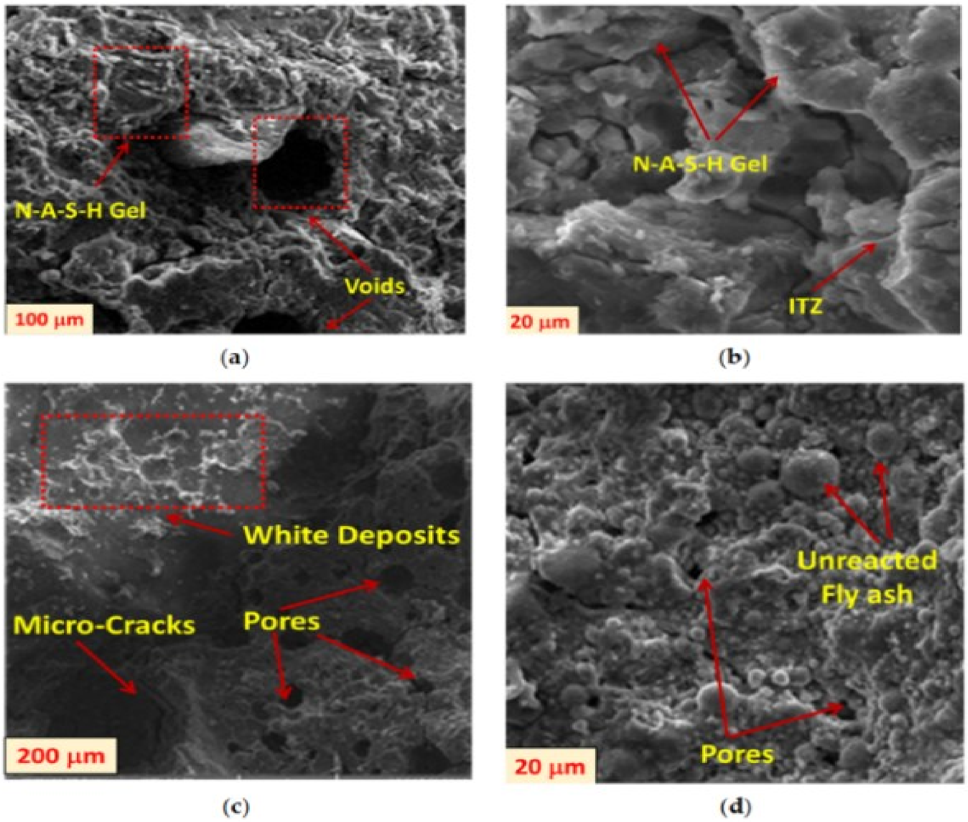

Fig. 13. SEM analyses of steam-cured HSGPC specimens: (a) appearance of voids; (b) presence of N-A-S-H gel; (c) presence of pores and cracks; (d) presence of unreacted fly ash and voids [20]

In high-performance geopolymer concrete (HPGC), the macroscopic mechanical and durability properties originate from a series of multiscale interactions that begin at the microscale, evolve through the mesoscale, and manifest at the macroscale. At the microscale, the chemical composition and reactivity of aluminosilicate precursors, together with the alkali concentration and Si/Al ratio, determine the type and density of the binding gels. Fly ash–based systems predominantly form N–A–S–H gels, while the incorporation of ground granulated blast-furnace slag (GGBFS) promotes the formation of C–(A)–S–H or hybrid gels, resulting in a denser matrix and faster strength development. A high gel fraction, low porosity, and homogeneous gel structure are key factors enhancing compressive strength and reducing permeability (Yu & Jia [46] ; Baskar et al., [47]). Unreacted particles may act as fillers that increase stiffness but can also induce local stress concentrations if they are coarsely distributed. The addition of nano–SiO_2 or silica fume further refines the gel structure, fills fine capillary pores, and improves the continuity of the binding network.

At the mesoscale, the interfacial transition zone (ITZ) between the geopolymer matrix and aggregates plays a crucial role in stress transfer and crack initiation. The ITZ in geopolymer concrete is typically denser and thinner than in ordinary Portland cement (OPC) concrete when the mix design and curing conditions are optimized; however, it can still act as a weak region when pore clustering occurs. The degree of pore connectivity determines the preferential pathways for fluid ingress and crack propagation. Incorporating steel, PVA, or polypropylene fibers introduces a crack-bridging mechanism that enables stress transfer across microcracks, delays crack propagation, and imparts ductile or strain-hardening behavior—distinct features of HPGC (Zhang et al., [48]).Thus, the mesoscale structure serves as a physical bridge linking the gel morphology at the microscale with the macroscopic mechanical response.

At the macroscale, both compressive

strength and elastic modulus increase with higher gel density, reduced porosity, and stronger ITZ bonding (Pilehvar et al., [49]). Post-cracking behavior and fatigue resistance depend on the fiber bridging mechanism and the energy required to rupture the gel bonds at the microscale. The gel chemistry of geopolymer binders—distinct from the C–S–H gel in OPC—provides superior resistance to acid attack, elevated temperatures, and chloride penetration. However, geopolymer matrices can be more sensitive to carbonation and moisture-induced degradation when the capillary network is highly interconnected (Bahmani et al., [50]). Therefore, controlling pore structure and ITZ quality is critical to maintaining long-term durability.

The correlations among the micro-, meso-, and macrostructural characteristics can be elucidated through advanced multiscale characterization techniques. Scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM/EDS) is used to examine gel morphology and the ITZ, while X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and nuclear magnetic resonance (NMR) analyses identify gel phases and Si–Al bonding environments. Mercury intrusion porosimetry (MIP) and X-ray computed tomography (X–CT) provide quantitative assessments of pore size distribution and connectivity. These data should be correlated with mechanical performance results, such as compressive, flexural, and fracture tests, to establish the relationships between structure and properties (Baskar et al., [47]). Overall, achieving high-performance geopolymer concrete depends on the ability to design and control its multiscale structure—optimizing gel chemistry, enhancing ITZ compactness, and reinforcing the matrix with nano-additives or fibers. The synergistic integration of these micro-, meso-, and macrostructural features underpins the exceptional strength, durability, and longevity of HPGC.

6. Mechanical Properties of HPGC

6.1. Strength of High-performance geopolymer concrete

Table 2. Overview of the compressive strength characteristics of GPC, HPGC [42]

No.	Geopolymer Mix Type	Activator Type	Curing Temperature	Compressive Strength	Reference
1	GGBFS and silica fume	Sodium silicate / sodium hydroxide	90 °C	130 MPa	[51]
2	GGBFS and fly ash	Sodium silicate / sodium hydroxide	20–25 °C	49.32 MPa	[52]
3	Fly ash and ground rubber	Sodium silicate / sodium hydroxide	60 °C	49.02 MPa	[53]
4	Fly ash and GGBFS	–	25 °C	50 MPa	[54]
5	Metakaolin and GGBFS	Sodium silicate / sodium hydroxide	27 °C	47.84 MPa	[55]
6	GGBFS	Sodium hydroxide	25 °C	36 MPa	[56]
7	GGBFS and rice husk ash	Sodium silicate / sodium hydroxide	80 °C	59.7 MPa	[57]
8	Metakaolin, fly ash, and silica fume	Sodium silicate / sodium hydroxide	25 °C	80.7 MPa	[58]
9	Laterite volcanic ash and metakaolin	Sodium hydroxide and sodium silicate	60–80 °C	49.72 MPa	[59]

Strength is among the most critical performance indicators commonly investigated in studies of high-performance geopolymer concrete (HPGC). The compressive strength of HPGC is influenced by multiple parameters, including curing temperature and duration, the type and composition of raw materials, the silicate-to-hydroxide ratio, alkali concentration, the silicon-to-aluminum (Si/Al) ratio, liquid-to-solid ratio, and the age of the concrete. Table 2 presents an overview of the compressive strength characteristics of geopolymer concrete.

Gautam [15] investigated the development of high-strength geopolymer concrete (HSGC) through 20 mix designs incorporating low-concentration sodium hydroxide solutions (3M, 4M, 5M, and 6M), using fly ash and ground granulated blast furnace slag (GGBFS) as precursors, and curing under ambient conditions. The study reported 28-day compressive strengths ranging from 50 MPa to 70 MPa. The 7-day strength reached 80–86% of the 28-day value, while ordinary Portland cement (OPC) concrete typically achieved only about 60%. The 7-day flexural strength of geopolymer concrete was found to be approximately 62–74% of the 28-day value, whereas OPC concrete generally attained only 39–44% (Table 3).

Table 3. 7-day and 28-day Compressive Strength of GPC and CC [15]

Strength (N/mm²)	Age	GPC Mix 3	GPC Mix 8	Conventional concrete M50	GPC Mix 15	GPC Mix 19	Conventional concrete M70
Compressive strength	7 Days	41.78 (77.87%)	54.99 (82.03%)	31.10 (59.80%)	56.90 (80.06%)	66.27 (92.23%)	39.25 (55.43%)
	28 Days	53.65	67.04	52.00	71.07	71.85	70.80
Splitting tensile strength	7 Days	2.78 (51.48%)	2.85 (49.56%)	1.94 (37.30%)	3.45 (58.27%)	3.76 (61.63%)	2.4 (44.03%)
	28 Days	5.4	5.75	5.20	5.92	6.10	5.45
Flexural strength	7 Days	3.8 (73.78%)	3.9 (74.42%)	1.95 (39.39%)	3.3 (61.11%)	3.76 (63.70%)	2.31 (44.42%)
	28 Days	5.15	5.24	4.95	5.40	5.90	5.20

Neupane et al.[11] produced two types of HPGC: the GP mix (70% fly ash and 30% GGBFS) and the HF mix (40% fly ash and 60% GGBFS), both cured at room temperature. Each mixture was prepared at target compressive strengths of 65 MPa and 80 MPa for comparison with corresponding OPC control mixes. The compressive strength development of HPGC was comparable to OPC concrete at early ages. From 28 to 90 days, HPGC exhibited an 18% increase in strength, while OPC concrete gained only 4% over the same period. For mixtures with equivalent compressive strength, the binder content required for HPGC was 20–25% lower than that of OPC concrete. Failure patterns under compressive loading indicated that HPGC specimens primarily fractured through the aggregates, suggesting a strong interfacial transition zone, while OPC concrete showed greater interfacial debonding. In terms of indirect tensile strength, HPGC exhibited similar early-age performance and exceeded OPC concrete at later ages. At equivalent compressive strength, HPGC also demonstrated higher tensile strength (Fig. 14).

M. Sherif et al. [6] evaluated the mechanical performance of HPGC mixes formulated with fly ash (FA), metakaolin (MK), and GGBFS. The study benchmarked these mixtures against conventional high-strength concrete (HSC). A mixture comprising 200 kg of MK and 300 kg of GGBFS exhibited the highest compressive strength at both early and later ages (63.3 MPa and 82.6 MPa, respectively), as well as the highest splitting tensile strength (6.2 MPa), flexural strength (9.2 MPa), and modulus of elasticity (37.68 GPa). The proportions of FA to GGBFS and MK to GGBFS significantly influenced strength development, with the 40:60 ratio yielding the optimal compressive and tensile strengths.

M. Rao et al. [21] developed an HPGC formulation incorporating 35% fly ash, 50% GGBFS, and 15% silica fume by binder mass, activated with a combination of sodium hydroxide and sodium silicate, and cured at ambient temperature. Copper-coated steel fibers and a high-range water-reducing admixture (Aur Amix 300) were also added. The mixture incorporating 2.0% steel fibers and a 14M alkali solution achieved a 14.5% higher compressive strength than the fiber-free counterpart, specifically reaching 63.95 MPa at 7 days and 91.36 MPa at 28 days. The results indicated that 2.0% steel fiber content was optimal for enhancing compressive strength.

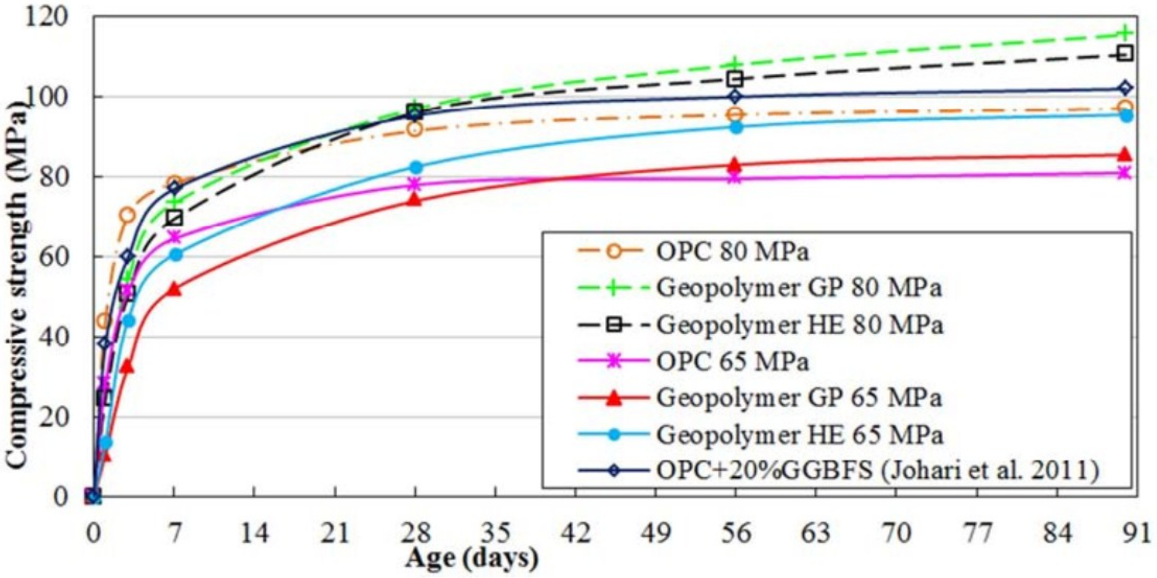

Fig. 14. Compressive Strength Development of Different Concrete Specimens [11]

In Vietnam, research on HPGC remains at the experimental and developmental stage at the laboratory scale. Preliminary results indicate that HPGC has the potential to achieve high compressive strength, typically ranging from 60 to 100 MPa, depending on the type of precursor materials used and the curing conditions.

The superior compressive strength of HPGC compared to OPC or HPC mainly arises from its distinctive microstructural features and gel formation mechanisms. The high CaO content in ground granulated blast furnace slag (GGBFS) plays a key role in strengthening the geopolymer matrix. The presence of CaO allows the material to harden at ambient temperature and promotes early strength gain through the rapid formation of C–S–H and C–A–S–H gels. In addition, the release of Ca^{2+} ions enhances the dissolution and polycondensation of aluminosilicates, leading to a denser C–(N)–A–S–H gel network.

Unlike low-calcium systems such as fly ash or metakaolin, which mainly produce N–A–S–H gels, the combination of fly ash and GGBFS generates a hybrid C–(N)–A–S–H gel with higher structural density and load-bearing capacity. This hybrid gel structure is a key factor behind the superior strength of HPGC compared with conventional concrete. Moreover, the interfacial transition zone (ITZ) in HPGC tends to be denser and more uniform, owing to the formation of calcium-rich gels surrounding the aggregates. This improves the bond strength and stress transfer across the interface, resulting in failure modes that occur through the aggregate rather than along the ITZ [11, 21, 60].

6.2. Elastic Modulus of HPGC

Table 4. Elastic Modulus of HPGC at 28 Days [11]

Binder ID	Grade 65 MPa		Grade 80 MPa	
	fcm (MPa)	Ec (GPa)	fcm (MPa)	Ec (GPa)
OPC	78.0	37.0	90.5	41.0
Geopolymer GP	73.5	37.0	91.5	39.0
Geopolymer HE	82.5	39.0	90.0	40.0

According to Neupane et al.[11] the elastic modulus is a fundamental mechanical property of concrete, as it directly affects the extent of deformation in structural components. A higher elastic modulus indicates a stiffer material and results in reduced deformation under applied loads. Previous studies have shown that geopolymer concrete typically exhibits a lower elastic modulus than OPC at equivalent compressive strength levels. However, their 28-day test results for high-strength concretes revealed that HPGC achieved an elastic modulus comparable to that of OPC concrete (Table 4).

In Vietnam, Tran Viet Hung [40] reported that the elastic modulus of fly ash-based geopolymer concrete (GPC) was lower than that of OPC concrete with similar compressive strength. Specifically, GPC exhibited elastic modulus values that were 2–14% lower according to ACI 363-11 and 10–30% lower based on AASHTO 2007 guidelines. This variation is attributed to the intrinsic differences in the binder systems between geopolymer and Portland cement. Furthermore, the disparity in elastic modulus tends to increase with higher GPC compressive strengths. Notably, the elastic modulus values of GPC reported in this study were higher than those of GPC produced in Australia, as reported by Hardjito [61], likely due to differences in fly ash composition and aggregate characteristics. These findings indicate that GPC is more deformable than OPC concrete under equivalent loading conditions. HPGC generally exhibits a lower elastic modulus than OPC due to differences in the microstructural characteristics of its gel phase and interfacial transition zone (ITZ). The primary binding gels in HPGC, mainly N–A–S–H or N–(C)–A–S–H, possess lower stiffness and a less ordered structure compared with the C–S–H gel in OPC, resulting in reduced elastic deformation capacity (Provis & van Deventer [13]). In addition, higher microporosity and non-uniform pore size distribution—arising from incomplete geopolymerization or moisture loss during heat curing—further contribute to increased overall deformability (Zhang et al.,[62]). Although the ITZ in HPGC is typically thinner and more homogeneous, its interfacial bonding strength may decrease in high-calcium systems or when using low-modulus aggregates, leading to early microcrack initiation under load (Nath et al., [63]). Taken together, these factors—the lower stiffness of the binder gel, intrinsic microporosity, and distinct ITZ characteristics—account for the generally lower elastic modulus of HPGC compared with OPC at equivalent strength levels.

6.3. Influencing the Mechanical Properties of HPGC

According to Nagarajan Arunachelam et al. [20], the compressive strength of high strength geopolymer concrete (HSGC) increased with the incorporation of silica fume up to 2%, due to enhanced homogeneity and a reduction in pore size within the matrix. At this optimal dosage, compressive strength improved by 38.7% under ambient curing and by 31.8% under steam curing. However, exceeding the 2% threshold led to a slight reduction in strength, which was attributed to the disruption of the geopolymerization process and an increased demand for Na_2O in the alkaline activator. With 5% silica fume, the strength gains were limited to 16.1% and 21.1% under ambient and steam curing, respectively (Fig. 15).

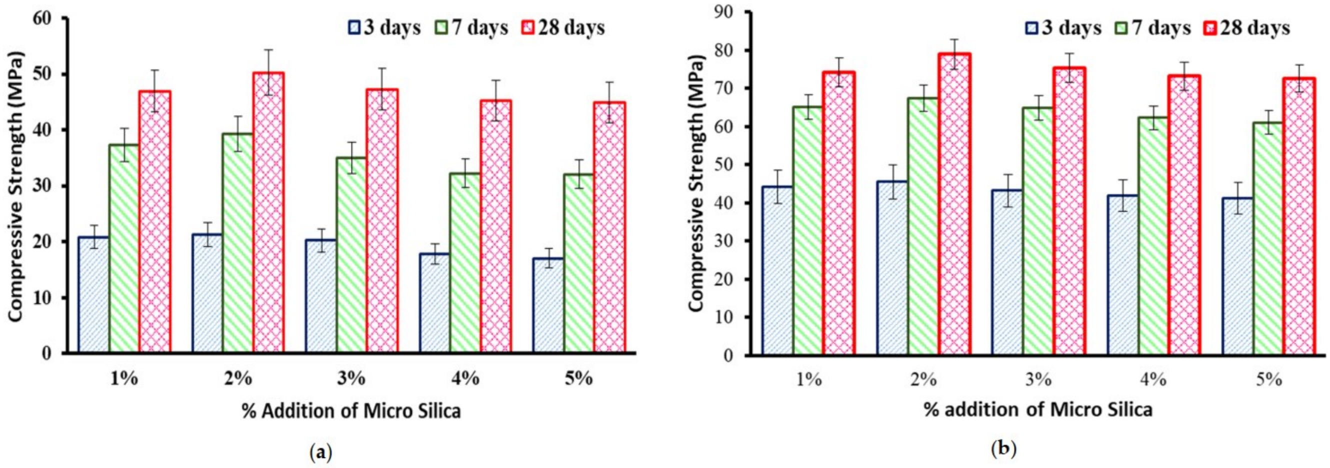

Fig. 15. Effect of micro silica on the strength of copper slag-based HSGPC. (a) Ambient-cured specimens. (b) Steam-cured specimens [20]

In the same study, compressive strength tests were conducted on high-strength geopolymer concrete (HSGC) in accordance with IS 516-1959, revealing pronounced differences between curing methods. Under steam curing, more than 80% of the ultimate compressive strength was achieved within the first 3 days, with only marginal increases thereafter. In contrast, specimens subjected to ambient curing exhibited a gradual strength gain over time, reaching the required strength only after 28 days. Compared to the control mix, the specimen containing 90% copper slag exhibited 33.5% and 62.2% higher compressive strength at 28 days under ambient and steam curing, respectively. Notably, the mix with 100% copper slag showed no detrimental effects and achieved even greater strength enhancements of 28.5% and 53.4%, respectively, under the same curing regimes. Consequently, the mix with 100% copper slag was deemed optimal and selected for further investigation with varying silica fume dosages (Fig. 16) [20].

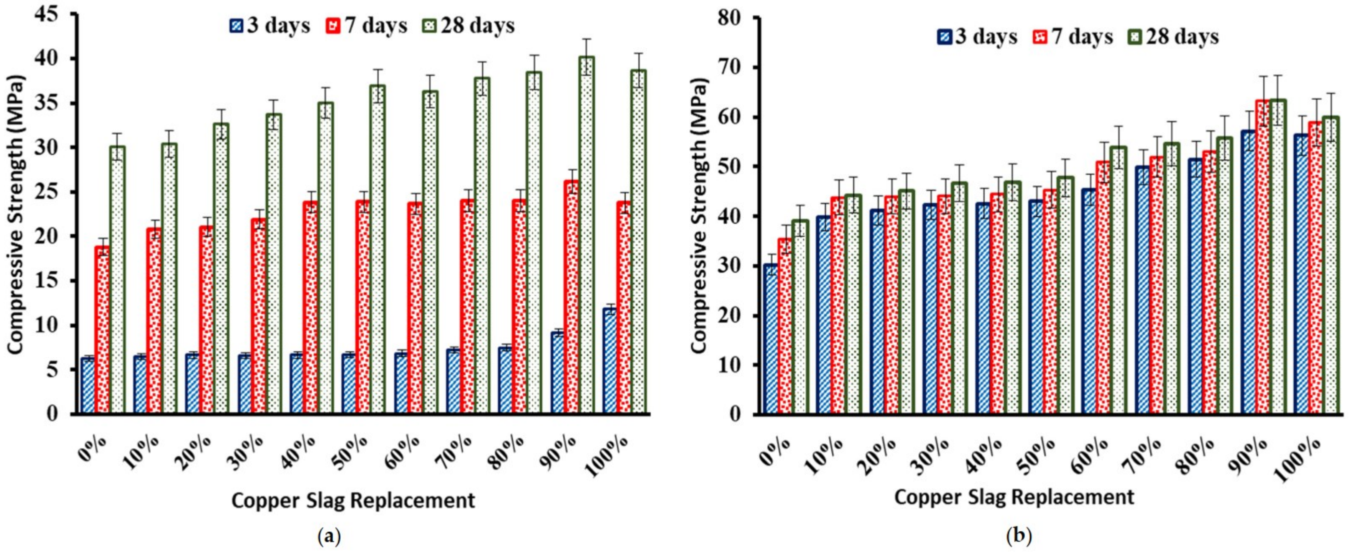

Fig. 16. Compressive strength of copper slag-based geopolymer concrete (HSGPC). (a) Ambient-cured specimens. (b) Steam-cured specimens [20]

In a subsequent study, M. Liu et al. [22] proposed a high-performance geopolymer concrete (HPGC) formulation without coarse aggregates, utilizing fly ash (FA), silica fume (SF), and ground granulated blast furnace slag (GGBFS) as binder constituents. The mix design was optimized using the Response Surface Central Composite Design (RSCCD) method to maximize both compressive strength and splitting tensile strength. The optimal formulation consisted of 15% FA, 10.30% SF, a Na_2SiO_3/NaOH ratio of 2.5, and a NaOH concentration of 10 M. Specimens were cast and initially cured at ambient temperature for 24 hours, followed by hot water curing at 80 °C for another 24 hours. Factorial analysis indicated that the factors influencing compressive strength, in descending order of significance, were NaOH molarity (FD) > Na_2SiO_3/NaOH ratio (FC) > SF content (FB) > FA content (FA). For splitting tensile strength, the order was slightly different: FC > FD > FB > FA.

In Vietnam, Tran Viet Hung [40] identified several key factors affecting the compressive strength of GPC. Extended mixing time led to increased strength, and higher curing temperatures generally enhanced strength development; however, temperatures exceeding 60 °C did not result in significant additional gains. Longer curing durations also improved geopolymerization and compressive strength, though most strength development occurred within the first 24 hours, with slower gains thereafter. Additionally, Pham Quang Dao [41] emphasized the notable impact of the water-to-binder ratio (W/B) on compressive strength. Increasing the W/B ratio from 0.48 to 0.51 resulted in a 14% reduction in 28-day strength, whereas decreasing it from 0.45 to 0.42 led to a 16% strength increase.

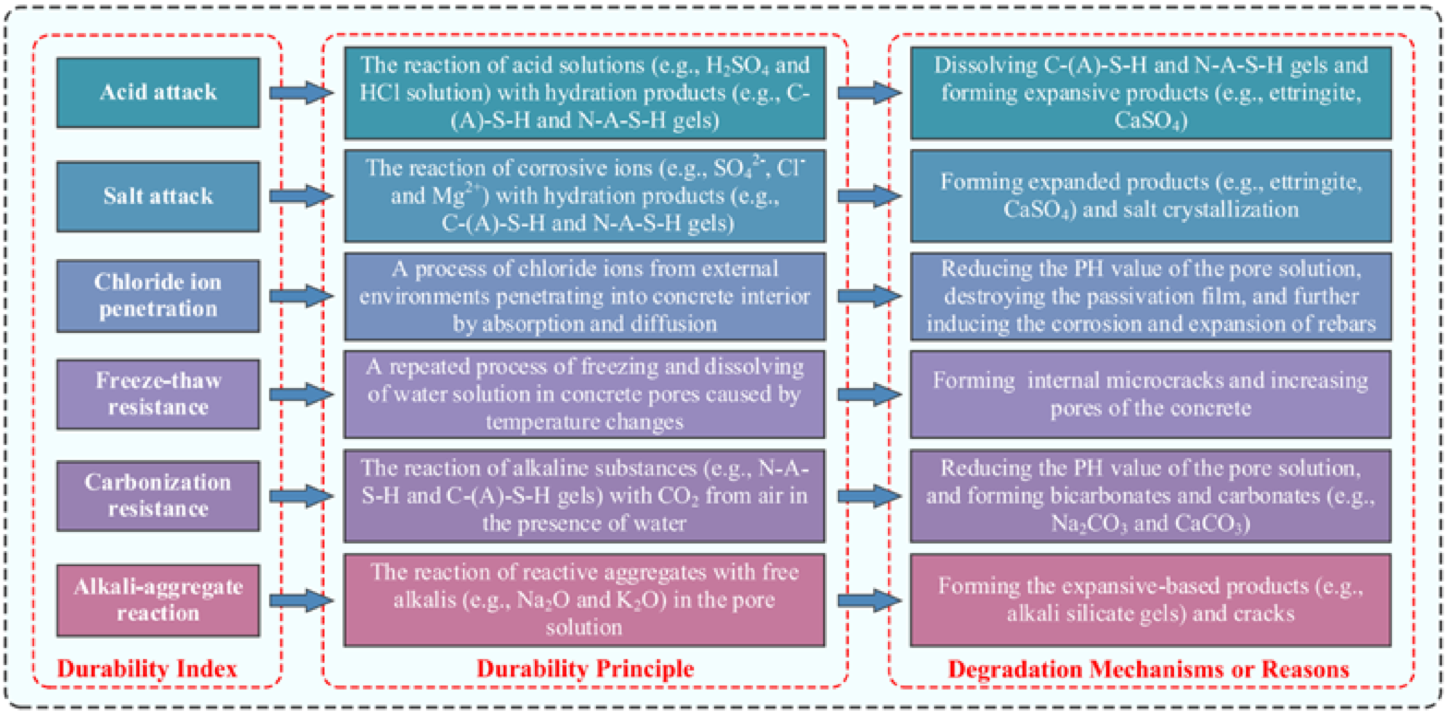

Fig. 17. Mechanisms and causes of degradation of HPGC under environmental exposure [64]

7. Durability of HPGC

Durability is one of the key advantages of high-performance geopolymer concrete (HPGC) over ordinary Portland cement (OPC) concrete, mainly due to its calcium-independent binder system, which lacks C_3A and CaO—compounds prone to acid and sulfate attack. Studies have shown that HPGC has lower permeability and superior resistance to acids, sulfates, and corrosion of steel reinforcement in marine environments. A common issue with OPC concrete is delayed ettringite formation (DEF), which occurs when the concrete is cured at elevated temperatures at early ages, leading to volumetric expansion and cracking. In contrast, HPGC, due to the absence of sulfates and calcium aluminates, is largely immune to DEF, even under high-temperature curing conditions [11] . According to Bai Zhang [64], geopolymer concrete generally exhibits better resistance to chemical attacks (e.g., acids and salts), chloride ion penetration, and freeze–thaw cycles compared to OPC concrete. However, it shows weaker performance in carbonation resistance and alkali–silica reaction (ASR). The durability and degradation mechanisms of geopolymer concretes depend on the raw materials used. Major degradation pathways include the dissolution of reaction products, formation of expansive phases, microcracking, and increased porosity, as shown in Fig. 17 with Sodium Alumino-Silicate Hydrate (N–A–S–H), Calcium (Alumino-)Silicate Hydrate (C–(A)–S–H).

7.1. Water absorption of HPGC

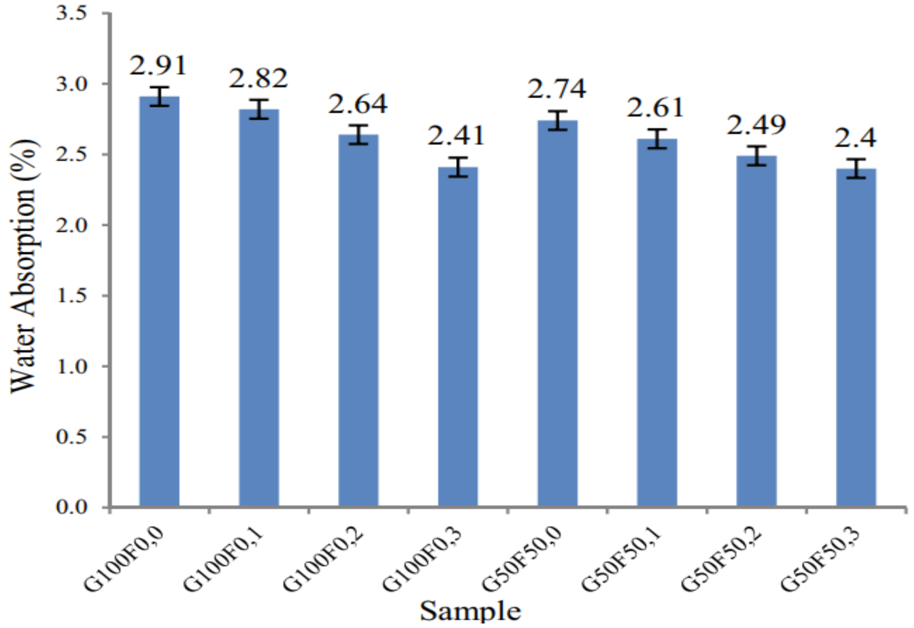

Fig. 18. Water Absorption at 28 days at different dosage of superplasticizer [65]

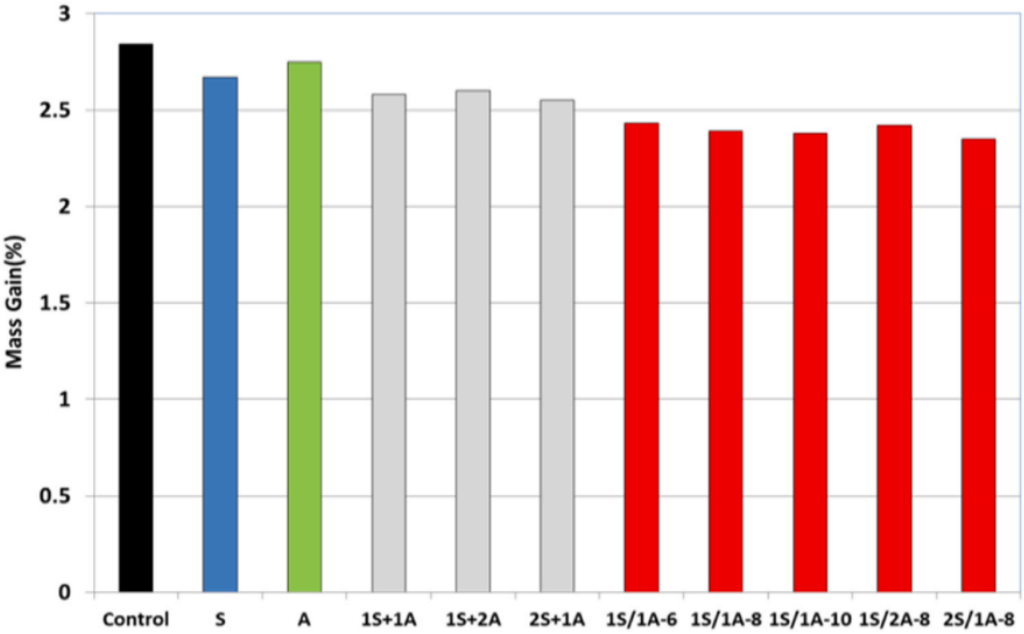

Fig. 19. Water absorption test results for the tested mixtures [45]

Nakul Gupta (2020) [65] found that water absorption in geopolymer concrete decreases with increasing superplasticizer content, attributed to the enhanced density of the concrete. Two groups of samples were prepared with varying superplasticizer contents (1%, 2%, and 3%). The first group used only GGBFS, while the second group combined 50% GGBFS and fly ash. The results indicated that water absorption decreased as superplasticizer content increased, with a minimum observed at 3% superplasticizer, as shown in Fig. 18.

Niyazuddin [66] evaluated the durability of normal and high strength geopolymer concrete using Particle Packing Theory (PPT) for aggregate optimization. Mixes designed with PPT showed markedly improved durability. The mix without PPT exhibited the highest water absorption. Water absorption decreased with higher GGBFS content, greater binder dosage, and increased NaOH concentration, due to finer particles filling voids and enhancing matrix density. The measured water absorption values (2.4% to 3.6%) aligned well with previous studies [67, 68]. Arab et al. [45] investigated the impact of nano-silica fume and nano-alumina blends—used both as physical mixtures and thermally treated additives—on the durability of high performance geopolymer concrete (HPGC).

The blends replaced 3% of fly ash at ratios of 1:1, 1:2, and 2:1, then underwent thermal treatment at 600°C, 800°C, and 1000°C. Results showed that incorporating and calcining the nano additives, especially at 800°C and 1000°C, significantly reduced capillary absorption and water uptake, improving impermeability. The control mix without nano additives recorded the highest absorption. The 1S/1A-8 sample treated at 800°C achieved a 15.4% reduction in capillary absorption and a 15.8% reduction in water absorption compared to the control (Fig. 19). High performance geopolymer concrete therefore exhibits significantly lower water absorption than conventional Portland cement concrete. This improvement can be attributed to the formation of an amorphous gel phase during the geopolymerization process, which fills internal voids, reduces porosity, and increases the microstructural density of the material.

7.2. Chloride Ion Penetration Resistance of HPGC

In coastal and marine environments, concrete structures are prone to deterioration due to ion ingress and acid attack. Chloride ion penetration is a common mechanism, occurring through capillary suction or hydrostatic pressure [69].

As shown in Table 5, The chloride resistance of high performance geopolymer concrete (HPGC) is primarily governed by its dense aluminosilicate matrix, which restricts chloride ion ingress and diffusion. Suitable alkaline activators and proper curing conditions enhance geopolymerization, forming compact N–A–S–H or C–A–S–H gels that refine pore structure and reduce pore connectivity. These gels can adsorb and immobilize free chloride ions, thereby lowering their mobility within the matrix. In addition, supplementary materials, nano modifications, and fiber reinforcement further densify the microstructure and limit crack development, which significantly improves resistance to chloride penetration, particularly in marine or chloride rich environments.

7.3. Sulfate Corrosion Resistance of HPGC

Kumar et al. [60] assessed the sulfate resistance of geopolymer concrete (GPC) and ordinary Portland cement (OPC) concrete by immersing cube specimens in 5% sodium sulfate and 5% magnesium sulfate solutions. Over a 24-week period, mass loss, compressive strength, and ultrasonic pulse velocity (UPV) were measured at regular intervals. GPC demonstrated better sulfate resistance than OPC, with lower mass loss and higher strength retention after prolonged exposure.

Ziada et al. [70] examined the combined effects of sulfate attack and freeze–thaw cycles on GPC incorporating metakaolin (MK), colemanite (K), and red mud (RM). Specimens were exposed to 5% sodium sulfate solution and 56 freeze–thaw cycles. Mixes containing K and RM showed higher initial mass loss due to sulfate reactions. “Sporosarcina pasteurii” bacteria were then used to heal microcracks via $CaCO_3$ precipitation. This self-healing process reduced water permeability and partially restored flexural strength, with calcium-rich mixes (KM and RMM) showing the highest recovery. The findings highlight the potential of bio-healing for GPC used in aggressive environments.

Table 5. Summary of Research Results on Chloride Ion Penetration Resistance of HPGC

No.	Type of Concrete	Factor	Key Materials / Parameters	Influence on Chloride Resistance	References
1	HSGC / HPGC	Composition of geopolymer binder	Fly ash, slag, metakaolin; Si/Al ratio	Higher Si/Al ratio promotes formation of dense N–A–S–H or C–A–S–H gel, reducing pore connectivity and chloride ion diffusion.	Sherif [6]; Neupane [11]; Sujitha [42]
2	HSGC	Supplementary mineral materials	Silica fume, copper slag, industrial solid waste	Fine particles improve particle packing and refine pore structure, significantly decreasing permeability and chloride diffusion.	Nagarajan Arunachalam [20]; Liu [22]; Niyazuddin [66]
3	Nano-modified HSGC	Nano-material modification	Nano-silica, nano-alumina	Nano-particles act as nucleation sites and accelerate geopolymerization, producing a denser matrix and improving resistance to chloride ingress.	Arab [45]
4	UHPGC	Particle packing and ultra-dense matrix	Quartz powder, silica fume, low water/binder ratio	Optimized particle gradation forms an ultra-dense microstructure with extremely low porosity, greatly enhancing resistance to chloride penetration.	Xu [38];Bahmani [50]
5	Fiber-reinforced HPGC / HSGC	Fiber reinforcement	Steel fibers, synthetic fibers	Fibers improve crack resistance and limit crack propagation, reducing pathways for chloride transport.	Ganesh [71]; Alrshoudi [72]; Liu [73]
6	HSGC / HPGC	Exposure environment	Marine water, chloride solution	Long-term chloride exposure mainly affects transport through pores and cracks; geopolymer concrete generally shows lower chloride diffusivity than OPC concrete.	Neupane [11]; Sujitha [42]

Table 6 summarizes the results, showing a tendency for high performance geopolymer concrete (HPGC) generally exhibits superior resistance to sulfate attack compared with ordinary Portland cement concrete. This behavior is mainly attributed to the chemically stable aluminosilicate gel network, such as N–A–S–H or C–A–S–H, which forms a dense matrix and limits sulfate ion penetration. Unlike the C–S–H gel in OPC that can undergo decalcification and lead to the formation of expansive products such as gypsum and ettringite, the geopolymer gel structure remains relatively stable in sulfate environments. In addition, the incorporation of supplementary materials, nano additives, and optimized particle packing further refines the pore structure and reduces permeability, thereby improving sulfate resistance.

Table 6. Summary of Research Findings on the Sulfate Corrosion Resistance of HPGC

No.	Author(s)	Type of Binder	Key Materials / Parameters	Exposure Environment	Influence on Sulfate Resistance
1	Sherif [6]; Rao [21]	High-strength geopolymer concrete (HSGC)	Fly ash, slag; geopolymer gel matrix	Sulfate-rich environment	Dense geopolymer matrix limits sulfate ingress, resulting in low mass loss and good strength retention.
2	Niyazuddin [66]	HSGC with alkaline activators	NaOH activator concentration	Chemical exposure conditions	Proper activator composition enhances geopolymerization and improves sulfate resistance.
3	Kanagaraj [74]	HSGC with mineral additives	Copper slag, micro-silica	Aggressive sulfate environment	Mineral additives refine pore structure and reduce permeability, limiting sulfate penetration.
4	Arab [45]	Advanced or nano-modified HSGC	Nano-materials and refined geopolymer matrix	Chemical aggressive environments	Dense gel network and refined pores enhance resistance to sulfate attack.
5	Xu [38];Bahmani [50]; Liu [22]	Ultra-high performance geopolymer concrete (UHPGC)	Silica fume, quartz powder, optimized particle packing	Sulfate solution	Ultra-dense microstructure significantly restricts sulfate ion diffusion and improves durability.

7.4. Carbonation Resistance and Alkali–silica reaction resistance of HPGC

Carbonation is a chemical process in which the hydration products of the binder react with atmospheric CO_2 to form carbonate compounds. This reaction decreases the alkalinity of the pore solution, disrupts the protective oxide layer on the reinforcing steel, and consequently accelerates corrosion. It also modifies the microstructure and mechanical behavior of concrete. Because natural carbonation occurs slowly, the accelerated carbonation test is often used to determine the carbonation depth, typically indicated by phenolphthalein staining [75]. Badar et al. [76] reported that HPGC made with low-calcium fly ash exhibited smaller pH reductions, indicating better carbonation resistance. Similarly, Khan et al. [77] observed that a mixture containing 90% low-calcium fly ash and 10% ground granulated blast-furnace slag (GGBFS) showed pH values of 9.8 and 9.2 under CO_2 concentrations of 1% and 3%, respectively, which were comparable to results under natural carbonation at 1% CO_2. C. Shi et al. [78] found that slag-based geopolymer mortar was more prone to carbonation than ordinary Portland cement (OPC) mortar; however, higher alkali content and silicate modulus improved its resistance by reducing total porosity. Zhuguo Li [79] also demonstrated that NaOH-activated GPC performed better against carbonation than that activated with a mixed NaOH–Na_2SiO_3 solution. Pasupathy et al. [80] highlighted that heat curing enhances carbonation resistance and minimizes early carbonation. Behfarnia and Rostami [81] further reported that replacing 15% of slag with silica fume significantly decreased the carbonation depth. Nonetheless, some studies have indicated that the carbonation resistance of HPGC remains lower than that of OPC concrete [75].

Alkali–silica reaction (ASR), often described as a progressive deterioration mechanism in concrete, arises from the interaction between hydroxyl ions in the pore solution and reactive silica in aggregates. This reaction forms an expansive gel that can induce cracking and compromise structural performance. Because high-performance geopolymer concrete (HPGC) is activated by alkaline solutions, understanding its vulnerability to ASR is essential for ensuring long-term durability. Several studies indicate that fly ash–based HPGC exhibits lower ASR susceptibility than ordinary Portland cement (OPC) concrete, largely due to its reduced calcium content and the development of a compact reaction gel (C.Shi et al. [78]). In contrast, slag-based systems or mixtures activated with highly concentrated alkaline solutions (greater than 8 M NaOH) may show expansions exceeding ASTM limits. The incorporation of fly ash, metakaolin, or the use of sodium silicate instead of NaOH can decrease pore solution alkalinity and limit the likelihood of ASR. Additionally, the inclusion of ground glass fibers (GGF), ferronickel slag (FNS), and appropriate exposure conditions has been reported further to enhance ASR resistance in geopolymer composites [75].

In Vietnam, several researchers have conducted foundational studies on the durability of GPC. Tran Viet Hung [40] produced fly ash-based GPC with compressive strengths of 30–50 MPa and evaluated its permeability, bond strength with steel reinforcement, and flexural behavior. Trinh Hoang Son [82] developed steel slag-based GPC with strengths of 25–35 MPa, modulus of elasticity of 25–30 GPa, Poisson's ratio of ~0.2, shrinkage of 300–400 με, thermal expansion of ~10×10⁻⁶/°C, and improved abrasion resistance. Doan Chi Hieu [16] used saline sand to produce GPC with 15–35 MPa strength; the mortar showed no expansion after 15 days in sulfate solution and no strength loss after 90 days in seawater, indicating excellent chemical durability. Dinh Hoang Quan [23] developed GPC with compressive strengths of 30–57.5 MPa, applied in a trial project on the Hai Hau sea dike, suggesting potential for coastal structures despite limited long-term durability data. Other studies include Vu Thanh Quang [83] on creep and shrinkage in GPC girders, and Le Hoai Bao [84] on the durability of GPC with recycled aggregates, promoting sustainable construction.

8. Environmental Impact Assessment of HPGC

M. Liu et al. [22] introduced a high-strength geopolymer concrete without coarse aggregate (HSGPC) and compared its carbon footprint to OPC, ultra-high-performance concrete (UHPC), and reactive powder concrete (RPC). Emissions were calculated as: $C_{etotal}=\sum(M_k \times C_{e}f_k)$, where M_k is the mass of each material and $C_{e}f_k$ its carbon emission factor. HSGPC showed the lowest emissions—30% lower than OPC, and 59.87% and 68.24% lower than UHPC and RPC, respectively. In HSGPC, emissions mainly originated from GGBFS, Na_2SiO_3, and NaOH, while in OPC-based concretes, over 90% of emissions came from cement. These results highlight HSGPC's dual advantage of low carbon emissions and high strength.

Kanagaraj et al. [74] conducted a comparative environmental assessment of high-strength alkali-activated concrete (HSAAC) and ordinary Portland cement concrete (OPCC) across three key aspects. Cost efficiency was evaluated based on the strength-to-cost ratio. The HSAAC mix (T18, with 50% GGBFS) showed a lower production cost (USD 85.96/m³) and higher efficiency (0.81 MPa/USD·m³) than OPCC (USD 93.28/m³; 0.71 MPa/USD·m³), indicating its economic viability (Fig. 20). Energy efficiency considered the embodied energy of raw materials.

OPC production consumes 4.53 GJ/t, while FA and GGBFS require only 0.033 and 0.857 GJ/t, respectively. However, alkali activators demand more energy—NaOH: 20.5 GJ/t; Na_2SiO_3: 5.371 GJ/t. The total energy for producing 1 m³ of both OPCC and HSAAC (T18) was approximately 2.831 GJ, although higher GGBFS content slightly increased HSAAC's energy demand (Fig. 21, Fig. 22). Eco-efficiency, based on CO_2 emissions, favored HSAAC. Its emissions (0.3571 t-CO_2/m³) were slightly lower than OPCC (0.3739 t-CO_2/m³). While OPC emits 0.73–0.85 t-CO_2/t, GGBFS and FA emit only 0.052 and 0.004 t-CO_2/t, respectively. Alkaline activators contribute significantly (NaOH: 1.915 t-CO_2/t; Na_2SiO_3: 1.222 t-CO_2/t). Despite similar strength-to-emission ratios, HSAAC presents a more sustainable alternative (Fig. 23).

Life cycle assessment (LCA) indicates that high-performance geopolymer concrete (HPGC) offers significant environmental advantages over ordinary Portland cement (OPC) concrete. Beyond carbon emissions, other critical indicators include embodied energy (EE), water consumption, and environmental toxicity. EE represents the total energy consumed throughout the material's life cycle, covering raw material extraction, production, use, and disposal. HPGC can reduce total energy consumption by 44–64%, with production EE about 3–7% lower than OPC. Specifically, the EE of FA (0.033 GJ/t) and GGBS (0.857 GJ/t) is substantially lower than that of OPC (4.53 GJ/t). However, EE is strongly influenced by the manufacture of alkaline activators, as producing 1 ton of NaOH and Na_2SiO_3 requires 20.5 GJ and 5.371 GJ, respectively. Consequently, embodied energy can make the overall environmental impact of HPGC higher than OPC in some cases (Balamurali Kanagaraj et al., [74]). Regarding water consumption, HPGC generally requires less water than OPC concrete (R. Bajpai et al., [85]), although some LCA studies (Habert et al., [2]) report that the production of activators such as FA, GGBS, and Na_2SiO_3 can increase water and energy demands. Toxicity impacts mainly arise from activator production, which can generate hazardous by-products contaminating soil and water (Yang et al., [86]). Overall, HPGC demonstrates clear benefits in reducing CO_2 emissions and total energy consumption compared with OPC concrete; however, enhancing its sustainability requires minimizing the embodied energy and toxicity associated with alkaline activator production.

In Vietnam, environmental assessments of GPC and HPGC remain limited. A critical next step is to establish a national emissions database for common binder materials such as fly ash, slag, and metakaolin under local production conditions. International collaboration and the adoption of LCA tools like SimaPro and GaBi are also essential for advancing sustainable material development.

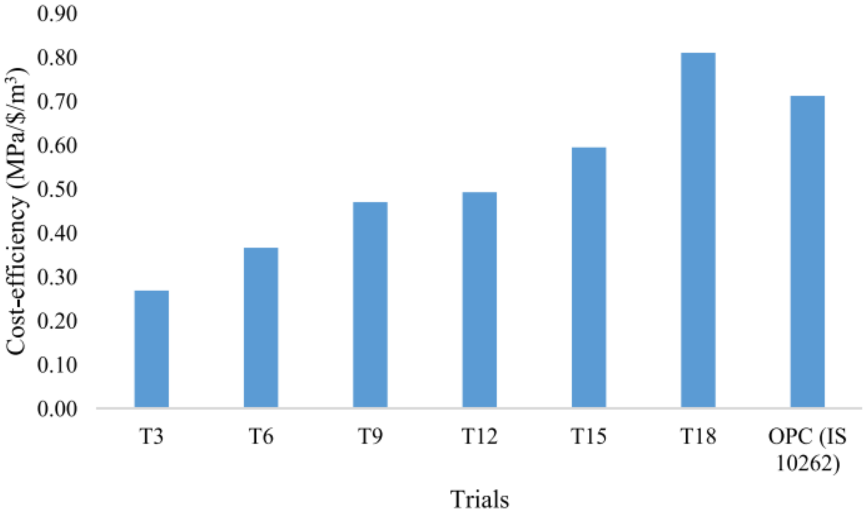

Fig. 20. Cost Efficiency of FA-GGBFS blended HSAAC [74]

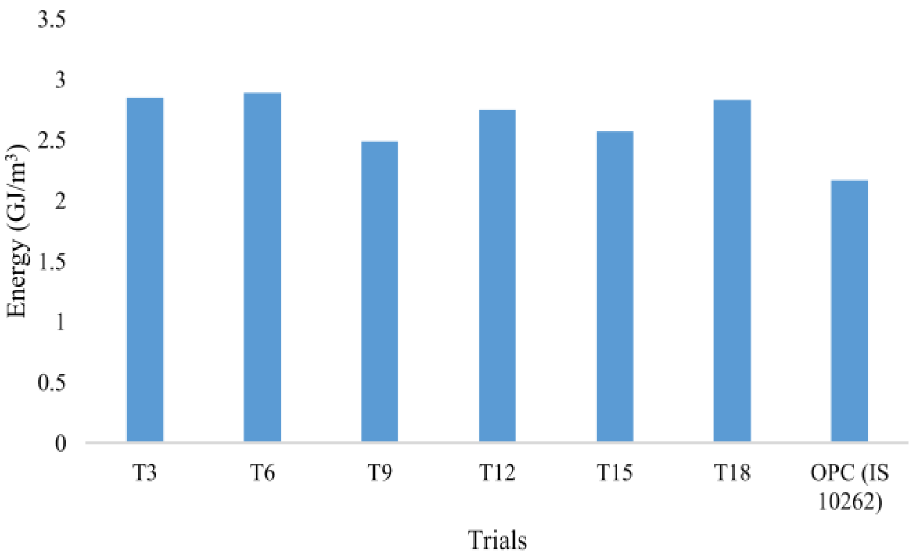

Fig. 21. Energy requirement for FA-GGBFS based HSAAC and OPCC [74]

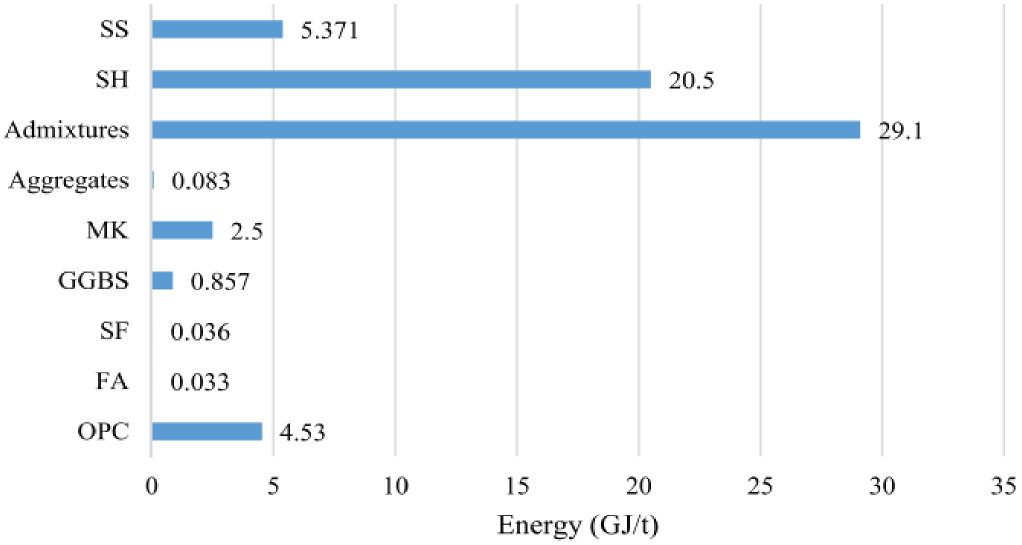

Fig. 22. The required energy of constituents' materials [74]

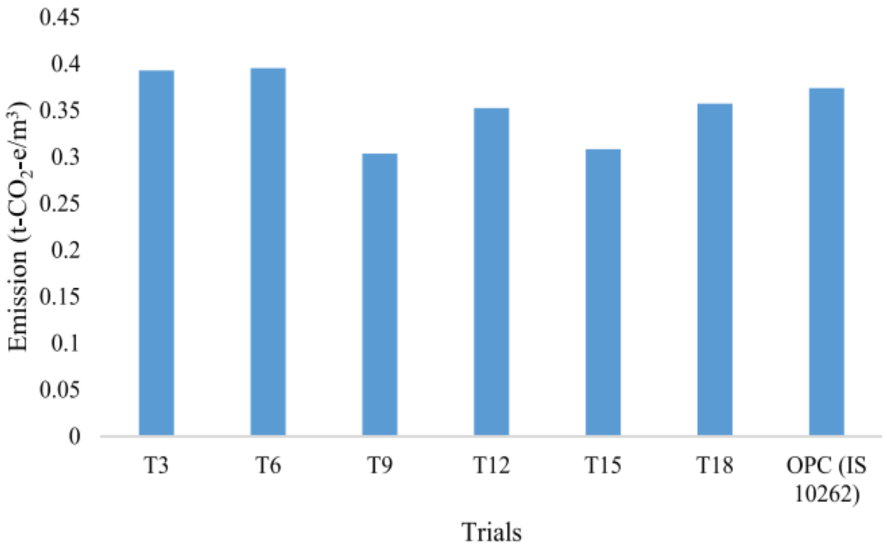

Fig. 23. Carbon emission assessment FA-GGBFS based HSAAC and OPCC [74]

9. Applications of HPGC

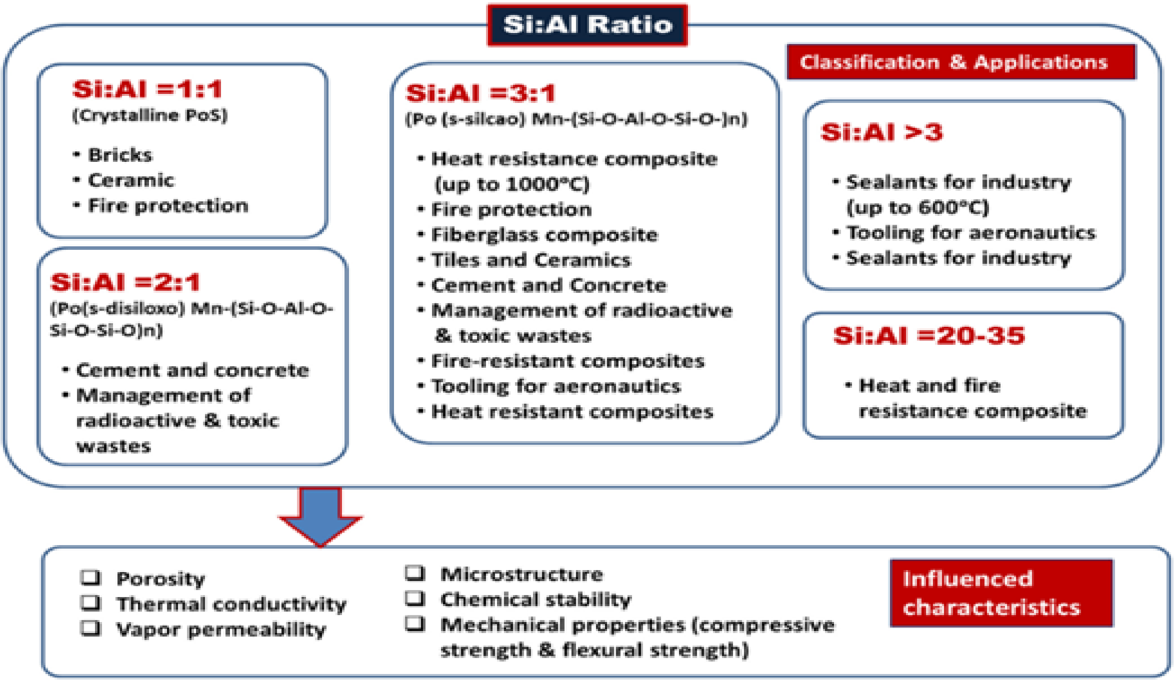

Fig. 24. Classification, applications, and influenced properties of geopolymers as a function of the Si/Al ratio [7]

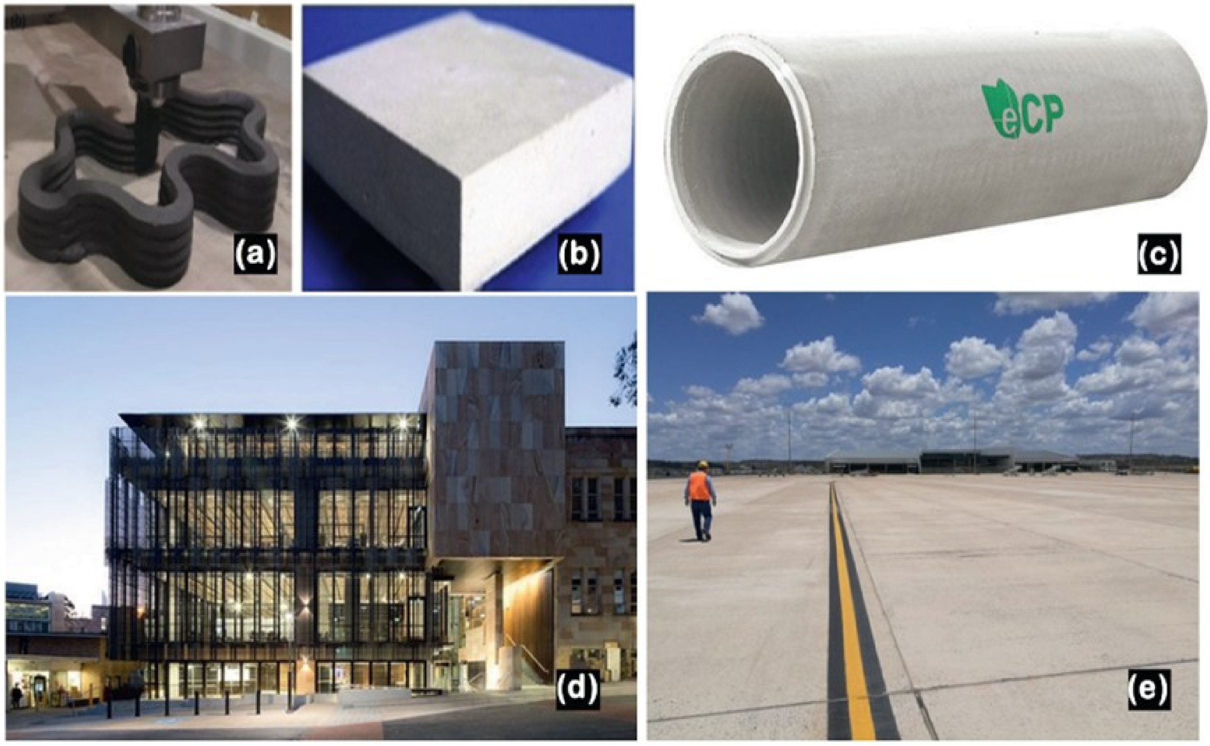

Fig. 25. (a) 3D printed geopolymer product, (b) geopolymer foam), (c) GeoC sewer pipes (RCPA), (d) the University of Queensland's Global Change Institute building using GeoC (CONSTRUCTOR), and (e) precast construction of GeoC (ALLPLAN) [6]

HPGC is widely used in infrastructure, high-rise buildings, heat-resistant structures, marine environments, repair and rehabilitation, precast elements, sustainable construction, and nuclear waste management due to its high strength, excellent heat resistance, and environmental benefits. The classification and application of geopolymer depend on the Si:Al ratio, which plays a critical role in determining the material's properties and applications, as shown in Fig. 24.

The strength-to-weight ratio reduces material usage and enhances overall structural performance [71, 72]. HPGC also offers resistance to chloride ion penetration and corrosion, making it suitable for marine environments. Its high early strength and fast curing time improve productivity and reduce curing time in precast production. This material is also well-suited for repairing bridges, parking structures, and high-temperature applications [73]. The diverse applications of GPC and HPGC in construction are illustrated in Fig. 25 and Table 7.

Table 7. Studies on the Applications of HPGC

No.	Product Name	Raw Materials	Manufacturing Method	Properties	Applications	Refs
1	Lightweight geopolymer concrete	Geopolymer binder, lightweight aggregates (expanded clay, perlite, GLAs), additives (H_2O_2, rice husk ash, scoria, nano alumina...)	Mix geopolymer binder with lightweight aggregates, additives, foaming agent (H_2O_2 or crushed foamed glass waste)	Low density, good thermal insulation, compressive strength 2.7–18.3 MPa, improved durability, thermal insulation, fire resistance, water resistance, high damping capacity	Lightweight structural elements, thermal insulation, sustainable construction	[87, 88]
2	Ultra-high performance geopolymer concrete (UHPGC)	Geopolymer binder, silica fume, quartz powder, steel fibers	Use the mix design of UHPC with geopolymer binder, add silica fume and 1–2% steel fibers	Compressive strength up to 120 MPa, improved mechanical properties thanks to silica fume and fibers	Load-bearing structures, high-strength requirements, extreme durability	[89, 90]
3	Self-healing geopolymer concrete	Fly ash, slag, nano-silica, sodium metakaolinite, self-healing bacteria	Mix geopolymer binder with additives that enhance self-healing capacity (e.g., bacteria or self-healing agents)	High mechanical strength, crack resistance, self-healing ability, extended service life	Structural elements requiring crack control, repair structures, durability, steel protection	[91, 92]
4	Geopolymer concrete for marine/coastal environments	Fly ash, slag, sand, alkali activators, geopolymer binder	Use geopolymer binder and coatings or additives to protect concrete surfaces	Resistant to acid, sulfate, seawater, chloride, low permeability, environmentally friendly	Marine structures, ports, coastal infrastructure	[93, 94]

In Vietnam, geopolymer concrete (GPC) has been studied and applied in various fields such as bridge and tunnel structures (Tran Viet Hung [40]), road pavements (Trinh Hoang Son [82]), and coastal revetments (Dinh Hoang Quan [23]). Other studies have focused on the production of non-fired bricks from red mud (Le Van Quang [95]) and geopolymer concrete incorporating recycled aggregates (Le Hoai Bao [84]). Numerical modeling and artificial intelligence have also been utilized to predict mechanical behavior and optimize mix design (Pham Quang Dao [41] ; Dinh Hoang Quan [23]). These studies have effectively utilized locally available industrial by-products such as fly ash, steel slag, ground granulated blast furnace slag, saline sand, and red mud to produce geopolymer concrete with compressive strengths up to 57.48 MPa.

However, research and application of high-performance geopolymer concrete (HPGC) in Vietnam remain at an early stage and face several limitations. Specifically, standardized mix design protocols for different precursor materials have not yet been established; pilot-scale or field-based investigations are lacking; and long-term durability data under tropical or marine exposure conditions remain limited. These represent critical gaps that need to be addressed in future research. In the coming years, the development of HPGC in Vietnam is expected to focus on producing materials with compressive strengths exceeding 60 MPa, aiming to meet the growing demand for sustainable, durable, and high-strength construction materials while reducing overall costs. Nevertheless, challenges such as long-term durability, creep, shrinkage, microstructural evolution, large-scale structural performance, production cost, and commercialization potential still require in-depth investigation.

10. Conclusions

Based on this review, the following conclusions can be made:

Materials for HPGC production: Low-calcium Class F fly ash is widely favored due to its fine particles, reactivity, and low cost. GGBFS allows ambient curing but is limited by coarse, inconsistent particles and higher cost. Metakaolin is highly reactive but increases water demand and porosity, raising costs. Rice husk ash and silica fume are also being explored to improve HPGC properties. Strong alkali activators (NaOH/KOH with Na_2SiO_3/K_2SiO_3) enhance strength, especially at higher concentrations and dosages.

Mix design and fresh properties of HPGC remain underdeveloped in Vietnam due to the absence of national standards. In contrast, international research has employed methods such as trial-and-error, response surface methodology (RSM), and optimization techniques. Some domestic studies are beginning to adopt these approaches. Despite its low water content, HPGC generally exhibits comparable or superior workability to conventional concrete. However, its high viscosity and stickiness pose challenges for long-term handling. Superplasticizers like naphthalene sulfonate or Auramix 300 significantly improve workability, whereas polycarboxylate-based admixtures are less effective.

Regarding mechanical properties, HPGC achieves compressive strengths ranging from 50 to 91 MPa and can exceed 130 MPa with thermal curing. It shows excellent early strength development. Key influencing factors include raw material type, silicate-to-hydroxide ratio, alkali concentration, and curing conditions. The elastic modulus is comparable to or lower than that of ordinary Portland cement (OPC) concrete. Failure typically occurs within the aggregate rather than the matrix, indicating a strong interfacial transition zone.

HPGC also demonstrates durability and microstructural characteristics. Its calcium-free binder system, lacking C_3A and CaO, provides excellent resistance to acid, sulfate, and chloride-induced corrosion—particularly valuable in marine environments. The material is less susceptible to delayed ettringite formation during high-temperature curing. Compared to OPC, HPGC shows superior resistance to acids, salts, chloride ions, and freeze–thaw cycles, although its resistance to carbonation and alkali–silica reaction (ASR) may be lower. Its low water absorption is attributed to a dense amorphous matrix, with further improvements achievable through nano-silica or superplasticizer incorporation.

From a sustainability perspective, HPGC offers a low-carbon alternative by utilizing industrial by-products instead of Portland cement. Its microstructure is marked by a dense, low-porosity matrix formed through N-A-S-H gel polymerization, and can be further enhanced by nano-additives such as nano-silica or nano-alumina. Owing to its high strength and superior chemical resistance, HPGC is highly suitable for infrastructure, marine structures, and precast components in sustainable construction.

Despite its advantages, HPGC faces several challenges and limitations. The absence of standardized testing methods and design guidelines—especially in Vietnam—impedes practical application and data comparability. The variable quality of raw materials (e.g., fly ash and slag) affects product consistency. Increasing demand may strain material supply, underscoring the need for alternative precursors. Moreover, acceptance within the construction industry remains limited, and full life cycle assessments are required to quantify the environmental benefits of HPGC.

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