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Review article

A state-of-the-art review of the physical and durability characteristics and microstructure behavior of ultra-high-performance geopolymer concrete

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ABSTRACT

This paper provides a comprehensive review of ultra-high-performance geopolymer concrete (UHPGPC), an innovative, eco-friendly, and cost-effective variant of ultra-high-performance concrete (UHPC), devised to meet the rising request for ultra-high-strength construction materials. Previous research papers have not thoroughly analyzed and compared the rheological, physical, durability, and microstructural properties of UHPGPC with UHPC. Similarly, review articles scarcely investigate UHPGPC's strength properties and microstructural behavior under high temperatures. This paper includes an assessment of the correlation between compressive strength, splitting tensile strength, and modulus of elasticity (MOE). The current study also compares chloride ion penetration test outcomes, elevated temperature, electrical resistivity, and porosity tests to evaluate durability. To analyze the microstructure of UHPGPC, the paper assesses results from Fourier Transform Infrared Spectroscopy (FT-IR), Thermogravimetric Analysis (TGA), Scanning Electron Microscopy (SEM), and Mercury Intrusion Porosimetry (MIP). The findings from the present paper suggest that UHPGPC effectively meets the ideal mechanical property specifications of UHPC. Compared to UHPC, UHPGPC displayed a higher ion passage propensity due to larger pores (>100 nm). Geopolymer technologies present a greener path for producing UHPC by consuming less energy and emitting reduced CO_2. Introducing mineral fillers like silica fume impacts the mixture's flowability and increases its water needs. However, adding an optimal ratio of micro-silica as a partial substitute for granulated blast furnace slag further bolsters the strength characteristics of UHPGPC. The strength of UHPC can also be notably improved by adjusting the water-to-binder ratio, with specific ratios yielding considerable enhancements in compression strength. The selection of an alkaline activator plays a pivotal role in UHPC's heat resilience. Among them, a combination of potassium hydroxide and sodium silicate is the prime chemical activator for boosting strength performance, durability behavior, and microstructural attributes, particularly at temperatures beyond 600 °C. Eco-friendly Geopolymer Composites (EGCs) offer lower embodied energy and CO_2 emissions than traditional composites, with certain components like polyvinyl alcohol fibers being key contributors to these emissions. Progress in self-healing materials is driving sustainability in construction through innovative

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techniques, such as bacterial applications and specific chemical reactions. The strength and workability of Engineered Geopolymer Composites are influenced by their fiber content, with certain fibers interacting weaker than others. On a microstructural level, UHPGPC has a relatively weaker structure than UHPC due to differences in pore size, but its durability is improved when reinforced with fibers.

List of abbreviations

OPC	Ordinary Portland Cement
UHPC	Ultra-high-performance concrete
UHPGPC	Ultra-high-performance geopolymer concrete
GPC	Geopolymer concrete
CO_2	Carbon dioxide
GBFS	Granulated blast furnace slag
FA	Fly ash
SF	Silica fume
MK	Metakaolin
SH	Sodium hydroxide
SS	Sodium silicate
RHA	Rice husk ash
CSH	Calcium-silicate-hydrate
QP	Quartz powder
SFs	Steel fibers
PPFs	Polypropylene fibers
PEFS	Polyethylene fibers
SEM	Scanning electron microscopy
MIP	Mercury intrusion porosimetry
TGA	Thermogravimetric analysis
FT-IR	Fourier transom infrared spectroscopy
w/c	Water to cement ratio
w/b	Water to binder ratio
VMAs	Viscosity modifying agents
WRP	Waste rubber powder
GW	Glass waste
MW	Marble waste
CG	Crushed glass
CC	Crushed ceramic
CR	Crumb rubber
NS	Nano-silica
MOE	Modulus of elasticity
HSC	High strength concrete
HPC	High performance concrete
STS	Splitting tensile strength
ER	Electrical resistivity
FRC	Fiber-reinforced concrete
RCPT	Rapid chloride penetration test
PVA	Polyvinyl alcohol fibers
ECC	Engineered cementitious composites
EGC	Engineering geopolymer composites
UHMWPE fibers	Ultra-High-Molecular-Weight-Polyethylene fibers
UPV	Ultra violet pulse velocity

1. Introduction

International data reveals that nearly 0.26 billion metric tons of ordinary Portland cement (OPC) are required yearly for building purposes [1]. As limestone serves as the primary raw material for the manufacturing of OPC, a critical scarcity of this resource could potentially arise within the next 2 to 4 decades [2]. In addition, producing one metric ton of OPC emits roughly an equivalent amount of CO_2, posing a significant environmental risk [3,4]. Ultra-high-performance concrete (UHPC) is a broad term encompassing a composite construction material comprising OPC, characterized by exceptional compression strength, increased toughness, and enhanced durability [5]. UHPC is predominantly appropriate for architecturally challenging structures, heavier bridges, high-rise structures, and buildings subjected to harsh surroundings [6–8]. Despite the strength and excellent durability of UHPC [9], apprehensions have been raised regarding its development due to the considerable usage of OPC, which contributes to elevated CO_2 emissions [10]. The content of OPC in UHPC typically ranges from 800 to 1150 kg/m^3, constituting twice or thrice the quantity found in standard concrete [11]. Consequently, the production of OPC demands significant natural raw materials and energy resources, leading to considerable carbon dioxide generation [12].

Consequently, the identification of an alternative binding agent is of utmost importance. A viable solution to this issue is using geopolymer concrete (GPC) [13]. The word “geopolymer" was introduced by Weitz in ‘78 to describe various materials characterized by networks of inorganic molecules. Table 1 offers quantitative information for estimating the embodied energy and CO_2 outflows of the materials employed in the formulation of UHPGPC. Geopolymers rely on materials that are rich in alumino-silicate, which include fly ash (FA), silica fume (SF), granulated blast furnace slag (GBFS), metakaolin (MK), integrated with a source of aluminum, and silicon [14–16]. The Al and Si are added to an alkaline chemical solution (carbonate, silicate, sulfate, and hydroxide) to initiate activation, followed by polymerization, during which the molecular chains develop adhesive properties [17,18]. The synthesis of geopolymer concrete with strength properties comparable to conventional concrete is achievable. Recent advancements in sustainable technology have driven efforts to develop ultra-high-performance geopolymer concrete (UHPGPC) using geopolymers as binding agents [19]. According to Prince et al. [20], incorporating 6 % Nano-silica into the GPC mixture containing FA and curing at 27° Celsius significantly enhanced the compressive strength of the resulting GPC. Kumar et al. [21] formulated GPC with FA, GBFS, and NaOH as an alkaline activator and demonstrated an 86 MPa compression strength when cured at 26° Celsius. Authors in a study [22] explored the substitution of rice husk ash (RHA) with FA and found that the optimal compression strength was achieved when 6 % RHA was replaced with FA. Additional research has examined GPC developed from GBFS [23–26]. Research [23–26] indicates that increased concentrations of $NaSiO_3$ and other alkaline substances increase Young’s modulus of the chemical activator, enhance the compression performance, and improve the workability of freshly mixed concrete while reducing the setting time. There is a limited body of comparative research between UHPGPC and UHPC. Notably, the primary components of UHPC binders are OPC and mineral fillers, with silica fume being a predominant example.

In comparison, UHPGPC binders predominantly comprise alkaline chemical activators and alumino-silicate-rich materials. Furthermore, the bonding between UHPC aggregates and cement paste is firm, and the microstructure is denser, making UHPC an ideal choice for high strength and exceptional durability characteristics. Ambily et al. [32] formed a UHPGPC using FA, SF, or GBFS as the aluminosilicate material, and $NaSiO_3$ and KSO_3 were employed to activate the UHPGPC. The authors observed the highest compression and bending strength of 174 MPa and 14 MPa, respectively. Middendorf et al. [33] examined the influence of SF as a fractional substitute for GBFS in producing HPGPC with the same content as MK. The authors achieved the highest compressive strength of 179 MPa by substituting 13 % of the GBFS with SF, while the compressive strength decreased in mixtures with 15 % SF. Guneet et al. [34] analyzed the arrangement of GPC with GBFS under various treatments. The authors discovered that samples treated with microwaves exhibited an enhanced compression strength than the air-treated specimens. Jumah et al. [35] evaluated the impact of ceramic aggregate on the performance of UHPGPC strengthened with SFs. Their findings revealed that mixtures incorporating ceramic aggregate engrossed higher energy than UHPGPC with no steel fibers.

In most studies investigating UHPGPC, GBFS has been employed as the primary alumino-silicate source, with NaOH and $NaSiO_3$ serving as activators [36]. Mineral fillers [37], including FA, SF, and GBFS, have been incorporated to improve the microstructural characteristics of the UHPGPC. Siliceous sand has been utilized as a fine aggregate. For the production of UHPGPC in most studies, alumino-silicate, SF, fine quartz aggregates, and quartz powder are blended in a mixture [38]. An alkaline chemical activator developed approximately 1 h prior is then introduced to the dry constituents, water, and admixture. The blending process is carried out until a uniform mixture is achieved [39]. Water-cured specimens are maintained at a constant temperature of 20° Celsius until the testing day. Conversely, steam-cured samples are placed at 90° Celsius for a 24-h duration prior to testing. The specimens undergo autoclave treatment, subjecting them to a pressure of 20 bar for 4 h, followed by continued treatment in water [40–42]. A summary of mixture designs of UHPC and UHPGPC established in various research can be found in Table 2. The chronological progression of UHPC

Table 1

Energy and CO_2 outflows of materials employed in the formulation of UHPGPC.

Refs.	Materials	Embodied CO_2 ($kg.CO_2/kg$)	Embodied Energy (MJ/kg)
[27]	Silica Fume	0.014	0.036
[28]	SH	0.016	3.0
[29]	HRWR	0.944	9.0
[30]	QP	0.024	0.85
[28]	FA	0.005	0.15
[28]	GBFS	0.083	1.60
[31]	SF	1.79	36
[28]	SS	0.016	3.0

SH – Sodium hydroxide, **HRWR –** High range water reducer, **QP –** Quartz Powder, **FA –** Fine aggregate, **GBFS –** Granulated blast furnace slag, **SS –** Sodium Silicate.

and GP over different stages is depicted in Fig. 1. Based on this illustration, the forthcoming research phase in this domain should focus on executing further comparative optimization and cost-efficiency analyses on GP binders. Over recent times, considerable investigation has been undertaken to augment the strength properties of GPC. Only a few studies have explored the evolution of ultra-high-performance geopolymer concrete [40,43–45]. The advancement of UHPGPC is crucial in satisfying the growing request for cost-efficient, high-performance, and sustainable materials in modern building practices. Consequently, the current research presents a comprehensive review of the physical, strength, durability, and microstructural characteristics of UHPGPC and the latest developments and viewpoints concerning UHPGPC.

Ultra-high-performance concrete and Ultra High-Performance Geopolymer Concrete are at the lead of advancements in the concrete technology world. These concretes are distinguished not just by their enhanced mechanical properties but also by their superior durability compared to conventional concrete materials. In conventional concrete, Ordinary Portland Cement stands tall as the primary binder. It forms the hydration products that give the concrete its strength and structure. However, with the advent of UHPC, there was a need to look beyond just OPC to achieve the desired properties. Silica Fume, a pozzolanic material, is known for its ability to densify concrete microstructure. SF contributes significantly to the enhanced strength and durability of UHPC. Looking at the mixes provided, the first two, sourced from Ref. [46], seem to have OPC as the primary binder and are supplemented by SF, Quartz Powder, and High-Range Water Reducer. The QP helps improve the packing density, thereby further contributing to the microstructure of the concrete. Notably, the first mix incorporates Steel Fibers (SFs), which bring ductility to the table. Fibers, especially steel, are known for enhancing the post-cracking behavior of concrete, adding to its toughness and durability.

Moving from the OPC-dominated world of UHPC to UHPGPC, there's a shift in the binder. Geopolymeric binders replace OPC, usually based on materials like Fly Ash (FA) and Granulated Blast Furnace Slag (GBFS). Geopolymers offer several advantages, including resistance to certain aggressive environments, reduced carbon footprint, and sometimes cost benefits. In the mixes from Refs. [47,48], GBFS seems to be the primary binder. However, they need to be activated to make geopolymers work, usually using alkalis. Sodium Silicate (SS) and Sodium Hydroxide (SH) fulfill this role. The ratio and amount of these alkali activators can influence multiple properties of the resulting geopolymer concrete, from setting time and strength development to long-term durability. The mixes from Refs. [38,49] present a blend of both worlds. They experiment with combinations of OPC and potential geopolymeric components, perhaps aiming to harness the benefits of both materials.

The essence of understanding and optimizing concrete mixes, especially those of UHPC and UHPGPC, stems from the foundational principle of particle packing. The Powers' Model, a revered and integral concept in concrete technology, profoundly influences the composition of these advanced concretes. According to Powers, the performance of concrete, both in terms of strength and durability, is closely tied to the total volume of voids present in the hardened matrix. The model highlights that achieving a dense microstructure with minimized voids or pores is pivotal, and this is realized through the adequate packing of particles of varied sizes. A densely packed matrix with minimal void space is obtained using materials ranging from larger aggregates to micro-sized additives. This densification plays a direct role in bolstering strength and enhancing the longevity of the concrete. In the context of the mix designs presented, materials like Ordinary Portland Cement, SF, FA, and QP aren't merely randomly chosen ingredients. They are methodically selected to optimize particle packing. Silica Fume, with its ultra-fine particles, fills in the spaces between the larger particles of OPC. Similarly, Quartz Powder aids in further refining the matrix, enhancing the overall packing density. This systematic selection ensures a progressive filling of voids, from the largest to the tiniest, resulting in a densified, strong, and durable matrix.

Table 2
Mix design of UHPC and UHPGPC.

OPC	SF	GBFS	MK	FA	QP	Sand	SS	SH	SFs	HRWR	Water	Refs.
950	285	–	–	–	173	690	–	–	117.75	24.5	155	[46]
950	285	–	–	–	173	690	–	–	–	24.5	155	[46]
–	–	950	–	–	456	684	171	114	157	19	–	[47]
–	–	950	–	–	342	798	171	114	157	19	–	[47]
–	–	950	–	–	342	–	171	114	78.5	19	–	[47]
–	–	950	–	–	342	–	171	114	–	19	–	[47]
–	–	950	–	–	228	912	171	114	157	19	–	[47]
–	–	950	–	–	228	912	171	114	78.5	19	–	[47]
–	–	950	–	–	228	912	171	114	–	19	–	[47]
–	180	652	–	145	–	905	314	45	156	–	87	[48]
–	270	652	–	127	–	905	314	45	156	–	87	[48]
–	90	652	–	163	–	905	314	45	156	–	87	[48]
–	45	688	–	172	–	905	314	45	234	–	87	[48]
–	45	688	–	172	–	905	314	45	156	–	87	[48]
–	45	688	–	172	–	905	314	45	78	–	87	[48]
–	45	688	–	172	–	905	314	45	0	–	87	[48]
–	235	750	–	–	220	885	214.3	85.7	–	45	150	[49]
–	–	–	985	–	220	885	214.3	85.7	–	45	150	[38]
–	235	985	–	–	220	885	214.3	85.7	–	45	150	[38]
–	235	–	750	–	220	885	214.3	85.7	–	45	150	[38]
–	235	750	–	–	220	885	214.3	85.7	–	45	150	[38]

OPC – Ordinary Portland Cement, **SF –** Silica Fume, **GBFS –** Granulated Blast Furnace Slag, **MK –** Metakaolin, **FA –** Fly Ash, **QP –** Quartz Powder, **SS –** Sodium Silicate, **SH –** Sodium Hydroxide, **SFs –** Steel Fibers, **HRWR –** High-Range Water Reducer.

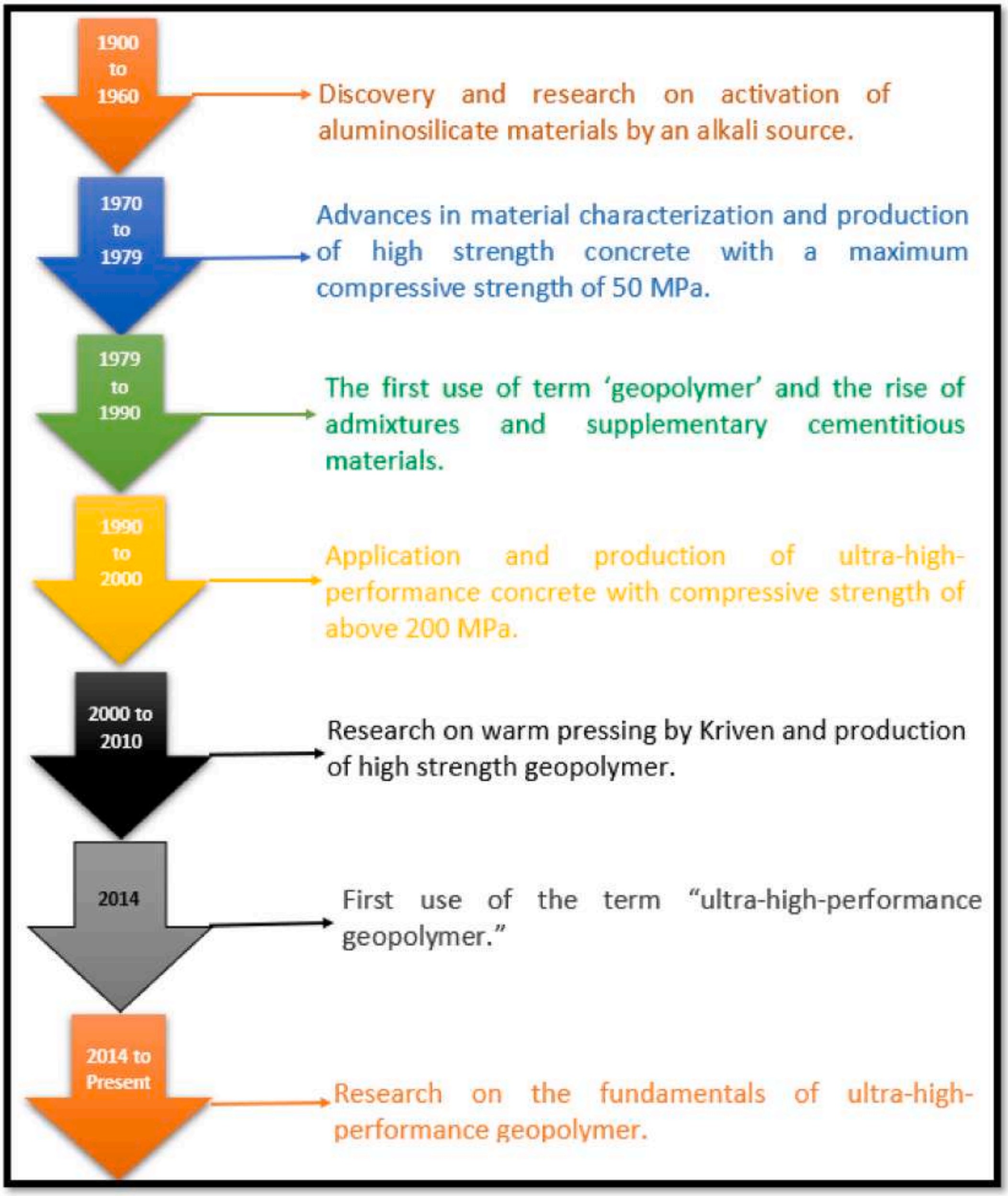

Fig. 1. Historical progress of UHPGP in chronological order [51].

Furthermore, when focused on the domain of geopolymers, the concept of geopolymerization becomes central. It's not just about particle packing but a more intricate chemical process. Geopolymerization involves a reaction where aluminosilicate materials, like Fly Ash or Granulated Blast Furnace Slag, engage with alkali activators such as Sodium Silicate and Sodium Hydroxide. This reaction forms a robust and durable binder, often seen as an alternative to traditional cementitious systems. The chemistry of geopolymerization is fascinating, given that it's temperature-sensitive and can be profoundly influenced by the type and concentration of activators. This chemical reaction bestows geopolymers' unique characteristics, including superior resistance to certain aggressive environments.

To summarize, fundamental theories like the Powers' Model guide the design of advanced concrete mixes. By understanding the distinctions between particle packing and the chemistry of geopolymerization, it becomes possible to engineer concrete that not only meets but often surpasses the desired performance criteria. Particle packing and geopolymerization reflect the intricate combination of science and engineering that goes into creating UHPC and UHPGPC, paving the way for next-generation infrastructural solutions.

While some of the characteristics of ultra-high-performance geopolymer concrete (UHPGPC) have been reviewed in a limited number of past researches [27,50], there is a lack of thorough studies examining the influence of various alkaline chemical activators and alumino-silicate-rich materials on the physical, strength, durability and microstructure characteristics of UHPGPC. Furthermore, no existing reviews compare the strength, structure, durability, and microstructural of UHPGPC and UHPC. Moreover, a thorough review of the strength properties and microstructural behavior of UHPGC subjected to elevated temperatures is scarce in the current literature. As a result, this review article aims to comprehensively examine the physical strength, durability, and microstructural characteristics of UHPGPC under different conditions. To completely characterize the microstructure of UHPGPC, scanning electron microscopy (SEM), thermogravimetric (TGA) analysis, Fourier-transom infrared (FT-IR) spectroscopy, and mercury intrusion porosimetry (MIP) test of UHPGPC were analyzed and reviewed. Over 160 research and review articles from major science and engineering databases, such as Elsevier, Nature, Wiley, Taylor & Francis, and MDPI, were collected, analyzed, reviewed, and presented in the current review paper. The study will offer thorough information about the present state of ultra-high-performance geopolymer concrete and address the current challenges and applications of the UHPGPC in the construction industry.

2. Design approaches of UHPGPC

Ultra-high-performance geopolymer concrete has captured the interest of researchers due to its potential as a more environmentally friendly alternative to ultra-high-performance concrete [33,51]. The primary method for producing UHPGPC includes (i) implementing pressurized or heat-assisted curing processes.; (ii) utilizing a GBFS and SF to achieve optimal workability and enhanced reactivity of alkaline chemicals at low precursor-to-water ratios [52]; (iii) raising the specific surface area while lowering the precursor particle dimensions [53]; and (iv) employing potassium-based alkali chemical as activators [54]. As the strength of UHPGPC is effectively developed through an alkaline chemical activator, it has the potential to serve as a feasible substitute for ultra-high-performance concrete in the construction industry, given its improved engineering properties. The properties of GPC are closely associated with the composition of the mixture. Crucial factors that impact the strength and durability properties of GPC include the alkali chemical-to-binder ratio, the SS concentration, the variety and proportion of alkali chemicals, and curing situations. The precise effects of numerous factors on the mechanical properties of GPC remain to be elucidated. Given the many components involved, developing a thorough mix design presents a significant challenge. Wu et al. [27] suggested a framework for devising an efficient preliminary mix for ultra-high-performance geopolymer concrete tailored to civil engineering applications. The researchers documented the development of an initial UHPGPC mix design utilizing chemically activated materials that are rich in alumino-silicates. The alkali chemical solution employed consisted of a combination of NaOH and $NaSiO_3$ solutions, while the alumino-silicates consisted of GBFS, RHA, SF, and FA. The investigation conducted by the authors utilized the target strength method for establishing the preliminary mix design of UHPGPC. Furthermore, Fig. 2 provides an in-depth illustration of their findings concerning the compression strength of GPC in relation to the w/b and the sodium oxide to binder ratio. This data is juxtaposed with the results proposed by Li et al. [55] for comparison purposes.

The proportion of each constituent in the precursor, encompassing ground granulated blast furnace slag, rice husk ash, fly ash, metakaolin, and silica fume, can be determined by employing the molar composition of their respective oxides. This approach allows for a comprehensive understanding of the individual components' contribution to the overall properties and performance of the resulting material. Nevertheless, it is crucial to cultivate an academic standpoint for the development and uniformity of GPC mix design to promote its adoption. In the study [53], the authors categorized the existing methodologies for the mixed design of GPC into 3 primary strategies: performance-oriented, statistical factorial, and targeted strength method. The procedure for devising a mix based on the desired strength comprises the following steps: (i) determining the alkali chemical-to-binder ratio or water-to-binder ratio in relation to compression strength, (ii) ascertaining the content of water or binder based on flowability or strength requirements; (iii) calculating the volume of fine aggregates according to the cement-to-aggregate ratio; (iv) adjusting the mix proportions to meet design purposes further; and (v) establishing the volume of coarse aggregates based on the sand-to-aggregate ratio to maintain appropriate

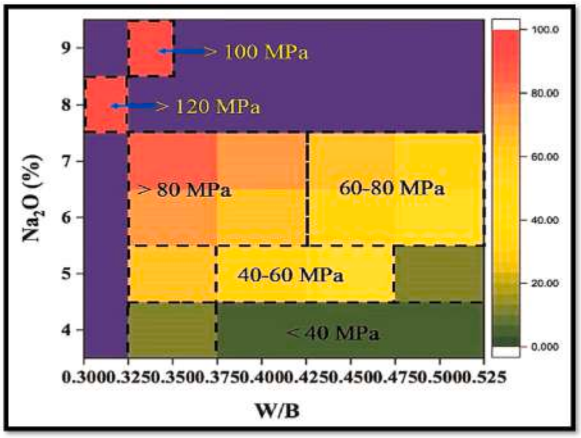

Fig. 2. The scope of compressive strength for GPC as a function of sodium oxide to binder ratio and w/b (Used as per permission from Elsevier [43]).

flowability. A performance-driven approach is more inclined to foster confidence in suppliers and convince consumers of the benefits of geopolymer or alkali-activated slag concrete. The statistical modeling technique used a sensitivity analysis to evaluate the impact of key factors on the properties of GPC, including the proportion of alkali, water-to-binder ratio, and chemical arrangement of precursors. In their conclusion, the researchers advocated implementing a performance-centered methodology for defining geopolymer or alkali-activated slag concrete, as the conventional approach concerning mix design and water-to-binder ratios elements couldn't be applied efficiently [58]. Subsequently, the appropriate mix proportions can be determined by utilizing the optimal values of these key factors.

3. Fresh characteristics of UHPGPC

Relative to traditional concrete, the polymerization process in GPC significantly diverges from the hydration process in plain cement concrete [59]. Consequently, standard additives, such as HRWR and VMAs (viscosity-modifying agents), are often ineffective. This leads to a more pronounced impact of the precursors and chemical activators employed in the mix. Numerous studies have substantiated that enhancing the ratio of alkaline activator, thereby reducing the pH of geopolymer binders, reduces the setting time. This enhancement reinforces the influence of mineral fillers, primarily FA, GBFA, RHA, SF, and MK, on the rheological properties of UHPGPC [32,43,47,60]. Multiple research studies have found that the water demand in UHPGPC with SF increases as the proportion of SF in the mixture increases [32,43,47,60]. This rise in water requirement can be attributed to the hygroscopic nature and higher SF surface area [61]. Per past studies [32,33], an increase in the content of SF in UHPGPC has been observed to cause a decrease in its expansion. The observed phenomenon is due to SF's role in decreasing free lime and magnesium in the mix. SF's lime content is also lower than GBFS's, further limiting expansion. Studies have shown that UHPGPC presents better fresh properties compared to UHPC. The enhanced rheology of UHPGPC is primarily attributed to its high w/b and the incorporation of alkaline chemical activators, which bestow a more fluidic nature upon the matrix as opposed to ultra-high-performance concrete, thereby facilitating its utilization in pragmatic applications. In one particular research, it was observed that the workability of UHPGC, measured by the slump, diminished with an increase in the concentration of FA, SF, and siliceous sand. This phenomenon may potentially result from the influence of these mineral filler materials, which exert a noteworthy impact on the rheological characteristics. Althoey et al. [16] revealed that adding Nano-silica significantly affected the flow diameter of UHPGPC. The authors observed that UHSGPC with 10 % Nano-silica (see Fig. 3) had an optimal effect during the flow diameter test.

UHPGPC mixtures with a high ratio of SF registered a slump measurement below 200 mm, which fell short of the minor workability threshold mandated by ASTM C1856 [62]. Introducing 1 %, SFs instigated a marginal alteration in the workability of nearly 10 mm. This can be ascribed to the optimized particle size distribution in the mixtures of UHPGPC. As the ratio of SFs rose, a discernible decline in the slump flow emerged, potentially influenced by the particle dimensions and morphology of the SFs [56], becoming intent amid the constituent particles. Rising the proportion of SFs from 1 % to 2 % lowered the slump of UHPGPC, possibly because of the enhancement in the specific surface area of the SFs, which consequently occupied a significant portion of the matrix [61,63]. It was also noted that the incorporation of quartz at the proportion between 20 % and 40 % results in flowability reductions of 22 %, 28 %, and 22.5 % for the percentage of SF of 0 %, 15 %, and 30 %, respectively. Althoey et al. [64] developed UHPGPC by incorporating various waste materials into its formulation. They found that the presence of WRP, GW, and MW substantially influenced the flow characteristics of UHPGPC. An intriguing observation was that the mix's fluidity improved with the incorporation of GW, with further enhancement seen as the proportion of GW was increased. This phenomenon can be attributed to the low water absorption capacity of the glass material and the reduced friction coefficient of GW, both of which contribute to an accelerated flow rate. From Fig. 4, it can be

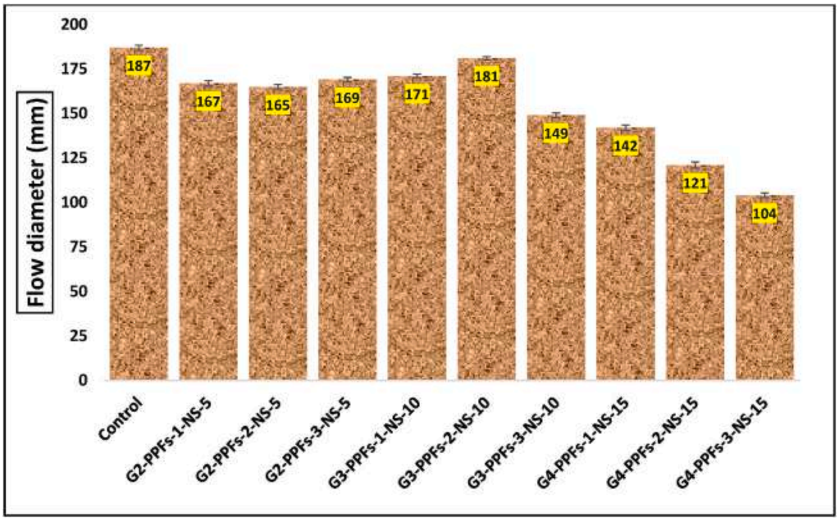

Fig. 3. Effect of Nano-silica on the flow diameter of UHSGPC (Data from Ref. [16]).

observed that the mixed flow without the additives measured 216 mm. However, with the integration of 5 %–15 % of GW into the mix, this value observed respective increases of 2.1 %, 3.9 %, and 4.42 %. Middendorf et al. [46] observed that the yield stress and viscosity of ultra-high performance geopolymer concrete specimens containing 5 %, 10 %, 12.5 %, 15 % silica fume, and 12.5 % SF exhibit the lowest values. This inclination, though, intensifies when the micro-silica concentration surpasses 15 % or reduces below 5 %. Shi et al. [31] revealed that raising the SF concentration from 10 to 20 % induces modifications in the rheology of UHPGPC, wherein an increased quantity results in reduced flowability, as shown in Fig. 5 The rheology of a mixture tailored for UHPGPC exhibits alterations when the fiber content ranges between 0 and 3 %.

4. Strength characteristics of UHPGPC

4.1. Compressive strength of UHPGPC

Incorporating various pozzolans into the ultra-high-performance geopolymer concrete mixture has yielded diverse outcomes regarding compression strength. When MK was employed as an alumino-silicate source in UHPGPC specimens, a compression strength reduction was observed compared to UHPGPC mixtures with GBFS [38]. This phenomenon could be attributed to MK's comparatively lower calcium ratio than GBFS. A high proportion of calcium in the aluminosilicate source enhances the potential for calcium-aluminum-silicon formation within the microstructure, consequently reinforcing the strength characteristics of the UHPGPC [65,66]. Excessive water content in UHPGPC mixes has been demonstrated to lower compression strength by undermining the progression of polymerization [67,68]. In UHPGPC, a w/b of 0.4 yielded a compression strength of 69 MPa, whereas a w/b of 0.25 delivered a peak compression strength of 199 MPa at 56 days [33], see Fig. 6. This underscores the significance of optimizing the w/b to achieve superior mechanical performance in UHPGC. The compression strength was observed to enhance as the ratio of SFs was raised in UHPGPC. Table 3 summarizes the details of the mixes and observed test outcomes from the past research. The authors in a study [60] incorporated 3 % SFs in UHPGPC and noted that the highest compression strength at steam and conventional curing was 170.3 MPa and 157.7 MPa, see Fig. 7 (a). This enhancement can be attributed to the steel fibers' ability to decelerate the development of macro and microcracking. However, steel fibers also lower the rheology of UHPGPC; therefore, adding more than 3 % SFs, despite the potential for increased compression strength, is not advised for the development of UHPGPC [69]. Under conventional curing conditions, an enhancement in compressive strength was observed in correlation with the fibers' length. However, when subjected to steam curing, increasing fiber length yielded contradicting outcomes (see Fig. 7 (b)) with respect to the compression strength, suggesting a complex interplay between fiber length and the curing process.

Althoey et al. [64] evaluated the compressive strength of UHPGPC modified with WRP, GW, and MW. The authors noted that at GW 15 %, the most enhanced compression performance of 179 MPa was observed after 90 days of curing, compared to the control sample with a strength of 161 MPa at the same duration. Adding 15 %, WRP reduced the compressive strength to 120 MPa at 90 days. At 56 days, adding 5 % GW led to a compressive performance of 154 MPa. AT 56 and 90 days, the compressive performance with 15 % GW led to 159 and 179 MPa. The dense matrix formed by SiO_2 in glass particles integrating with the geopolymer matrix contributed to higher compressive strength (see Fig. 8). Tahwia et al. [70] assessed the compressive strength of UHPGPC by substituting the fine aggregates with crushed glass (CG), crushed ceramic (CC), and crumb rubber (CR). The compressive strength development was found to be affected by the integration of waste materials. A 7.5 % replacement resulted in the maximum compression strength at 28 days for CG1 (149 MPa), similar to the reference mixture (152 MPa). However, as the CR was incorporated, the 28-day compressive strength decreased to its lowest point (102 MPa). The addition of 7.5 % CC reduced the 28-day strength capacity from 152 MPa to 131 MPa. The authors noted that these waste materials' irregular shapes and textures might result in a less compact and dense concrete mix, affecting the overall mechanical performance. Additionally, crumb rubber, a more flexible and less stiff material, can reduce the load-carrying

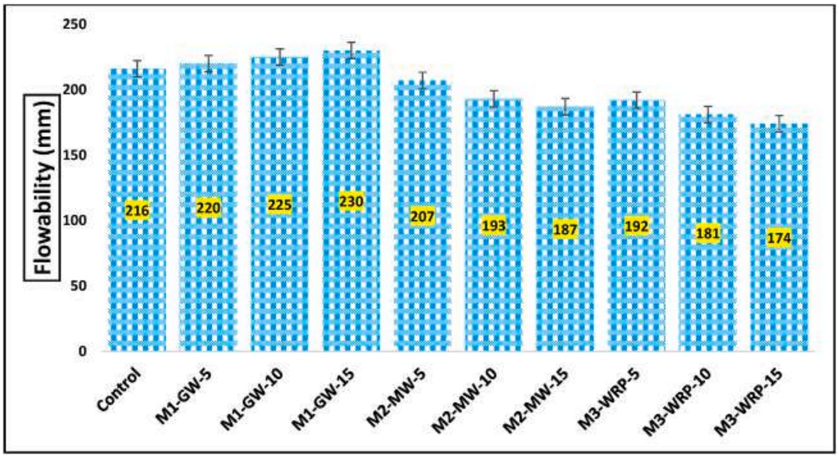

Fig. 4. Flowability of UHPGPC modified with GW, MW, and WRP (Data from Ref. [64]).

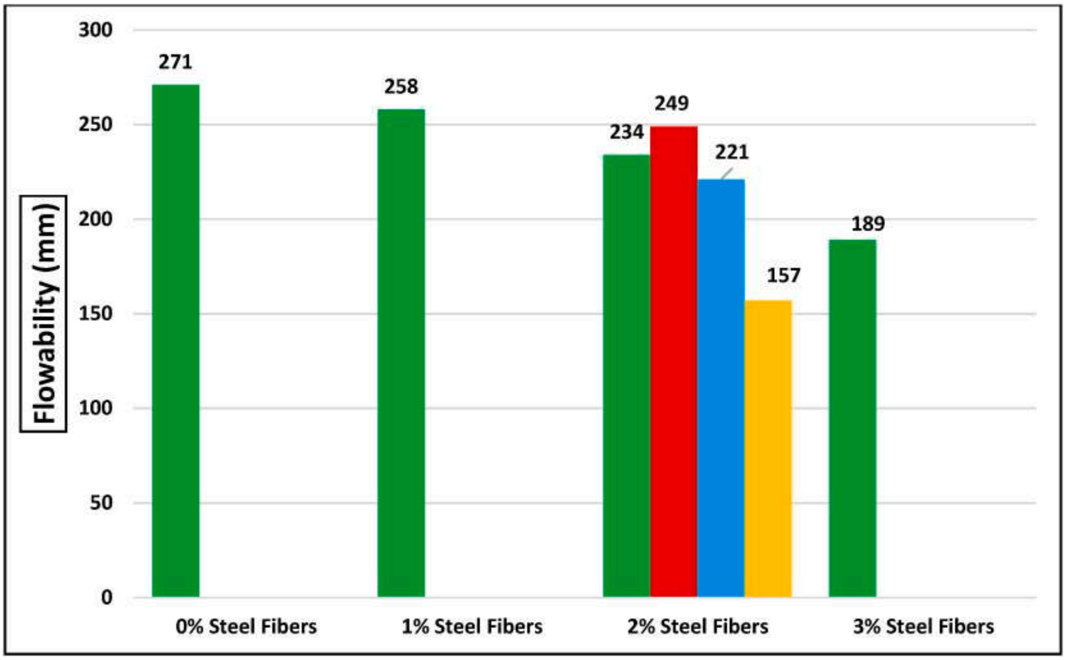

Fig. 5. Effect of different percentages of SF and steel fibers on the flowability of UHPGPC (Date from Ref. [48]).

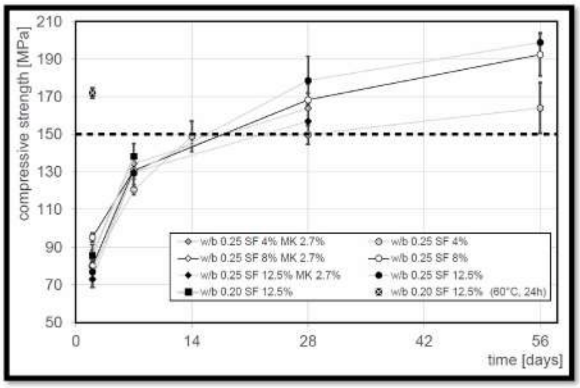

Fig. 6. Compression Performance of UHPGPC with several percentages of MK and SF (Used as per permission from Elsevier [33]).

capacity of the concrete matrix. Also, the bonding amid the waste materials and the geopolymer matrix might not be as strong as that between the fine aggregates and the matrix, leading to weaker interfacial zones and, consequently, a decrease in compressive strength.

4.2. Load-deflection behavior and flexural performance of UHPGPC

Steel fibers are recognized as essential materials to enhance the ductility and flexural characteristics of conventional and geopolymer concrete materials [76]. Wu et al. [52] reported that a mere 1.5 % SFs in ultra-high-performance geopolymer concrete could enhance the flexural fracture energy by 30-fold. However, it is worth noting that such minimal quantities influence the brittleness of UHPGPC [57]. Liu et al. [71] conducted a study to examine the influence of steel fibers on the fracture and strength properties of ultra-high-performance geopolymer concrete. The authors employed 3 distinct volume fractions of SFs (0 %, 1 %, 2 %, and 3 %), and 4 silica fume volumes (5 %, 10 %, 20 %, and 30 %) were employed by binder's mass. The researchers found that incorporating SF into UHPGPC enhances fracture and strength, including compression, splitting tensile and flexural strength, fracture resistance, and modulus of elasticity. The increase in SF content substantially improves the strength performance of UHPGPC, corroborating previous research on Portland Cement-based UHPC [77]. The enhancement can be attributed to adding more silica fume, which reduces the average distance between individual fibers and enhances the interfacial pressure between the fibers and the matrix. This ultimately diminishes the initiation and propagation of cracking in the material. The volume of SF plays a crucial role in influencing the binder's

Table 3
Objectives and findings of recent research on UHPGPC.

Objectives of Work	Conclusion	Ref.
Ceramic ball aggregate UHPGPC	Compared to conventional UHPGPC, UHPGPC modified with ceramic ball aggregates exhibited higher impact resistance.	[71]
Durability of UHPGPC	Swapping steel fibers with PPFs results in lower strength performance of the material. In addition, incorporating steel fibers into the mixture elevates the electrical resistivity of the passing flow, while polypropylene fibers have the opposite effect and decrease it.	[72]
Influence of PPFs and SF on the strength properties of UHPGPC	The fracture properties decrease with increasing silica fume concentration up to 10 %, but they tend to rise beyond that threshold.	[73]
Impact of the ratio and kind of steel fibers on the ductility of UHPGPC	The addition of steel fibers to a material reduces its flowability. However, using higher concentrations of steel fibers in smaller diameters can enhance the material's mechanical properties. Interestingly, incorporating steel fibers with a high deformation ratio had a minimal effect than plain steel fibers.	[60]
Fracture toughness of UHPGPC	The addition of fibers can significantly enhance the fracture energy, with an increase of up to 27x higher than that of a fiber-free counterpart. By incorporating polyvinyl alcohol fibers into the GPC, an ultra-high tough GPC can be produced. However, increasing the curing temperature results in a decline in fracture energy while simultaneously enhancing the MOE of the material.	[74]
Strengthening UHPGPC with glass fiber-reinforced polymer	The incorporation of glass fiber reinforcement significantly improved the resistance of the concrete to deformation, reduced the occurrence of cracks, and influenced the formation of crack patterns.	[75]
Development of eco-friendly UHPGPC	Replacing Silica fume with slag leads to an increase in the consistency and uniformity of the mixture. The addition of silica sand reduces the workability of the mixture. The assessment of compression performance heavily depends on the presence of steel fibers, silica fume, and silica.	[47]
Development of UHPGPC in ambient surroundings	The manufacturing cost of UHP-GPC is anticipated to exceed that of conventional UHPC. The mixtures formulated for UHPGPC exhibit a relatively longer setting time, typically 40–60 min. The use of SFs plays a vital role in the development of UHP-GPC.	[32]

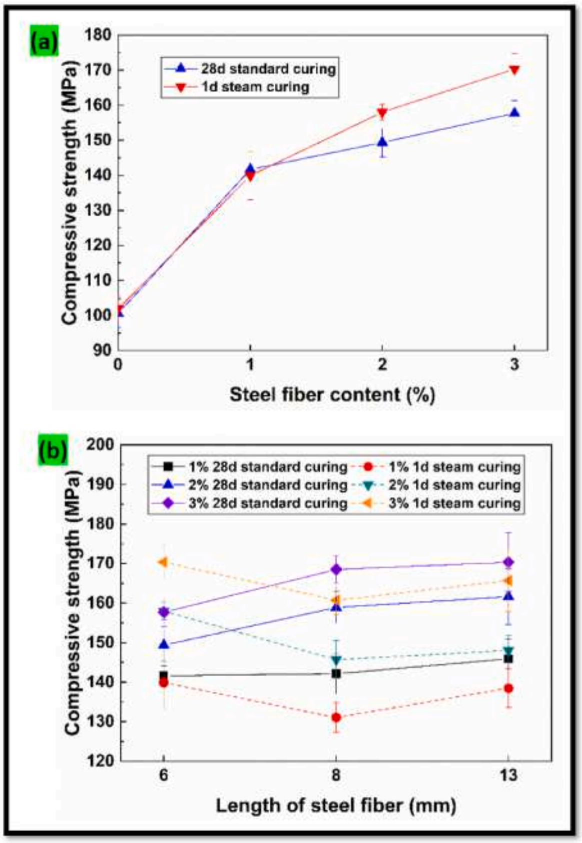

Fig. 7. Effect of Steel Fibers on Compressive Strength of UHPGPC; (a) Percentage of SFs, (b) Length of SFs (Used as per permission from Elsevier [60]).