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Experimental Study of Mechanical Properties of Geopolymer Concrete as Green Concrete with a Sustainable Development Approach in the Construction Industry, Under High Temperature

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Abstract

Today, the use of processed mineral materials in concrete to improve mechanical properties and durability has opened a wide field of vision for researchers in the structural sciences. On the other hand, preserving the environment by reducing the toxic gas of carbon dioxide caused by cement production is one of the concerns of scientists. In this regard, minerals containing abundant aluminosilicate particles and active alkali solution (AAS) replaced ordinary cement in concrete and led to the production of geopolymer concrete (GPC). The composition and reactivity of these materials produce a strong adhesive material that in combination with other concrete components, causes the final strength of GPC. High temperatures weaken the concrete against loads by damaging the structure of hydrated gels in concrete. GPC has better fire resistance than OPCC due to its density in its microstructure. In the current study, Granulated Blast Furnace Slag (GBFS)-based GPC was used with 0-2% polyolefin fibers (POFs) and 0-8% Nano silica (NS) to improve its structure. After curing the specimens under dry conditions at a temperature of 60 °C in an oven, they were subjected to Compressive strength, Modulus of *elasticity* and Weight Loss tests to evaluate their mechanical properties. all tests were performed at 90 days of age under ambient temperature (20 ℃) and high temperature (500 ℃). The addition of NS enhanced the whole properties of the GBFS-based GPC. Addition of up to 8% NS to the GPC composition at 20% temperature improved the modulus of elasticity test results by 13.42% and the compressive strength up to 21.94% by 11.58%. Addition of up to 2% of POFs to the GPC composition resulted in an improvement, modulus of elasticity of 07.05% and a decrease in compressive strength of up to 22.49%. Apply the lowest (0.061%) and highest (0.12%) weight loss percentage of concrete samples under 500% heat, belonging to scheme 4 (including GPC containing 8% NS) and scheme 6 (including GPC containing 2% POFs) Came. In the following, by conducting the Slag, Scanning Electron Microscope (SEM) analysis, a microstructure investigation was carried out on the concrete samples. In addition to their overlapping with each other, the results indicate the GPC superiority over the regular concrete. Besides, it demonstrated the positive influence of NS addition on the concert microstructure. (DOI:https//**doi.org/10.52547/JCER.4.4.1**)

Keywords **:** Geopolymer Concrete, Polyolefin Fibers, Nano Silica, Granulated Blast Furnace Slag, Scanning Electron Microscope.

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1. Introduction

Currently, considering global trends and challenges, as well as the UN[1] sustainable development goals and the ESG[2] plan, the development of geopolymer binders for the production of GPC has become an urgent area of construction science [1]. GPC is one of the innovative eco-friendly materials that has gained the attention of many researchers in the sustainable development of the construction industry [2]. GPC is a new material in the construction industry, with different chemical compositions and reactions involved in a binding material. The pozzolanic materials (industrial waste like fly ash, ground granulated blast furnace slag), which contain high silica and alumina, work as binding materials in the mix. GPC is economical, low energy consumption, thermally stable, easily workable, eco-friendly, cementless, and durable [3]. GPC is an environmental friendly concrete as it relies on minor treated natural materials or industrial wastes like (Fly ash, GBFS and silica fumes etc) which are having high alumina and silica content, to significantly reduce the carbon footprints [4]. GPC is produced from the geopolymerization process, in which molecules known as oligomers integrate to form geopolymer networks with covalent bonding [5]. Materials research has shown GPC has the potential to significantly improve the sustainability of concrete construction [6]. GPC has superior mechanical and durability properties compared to ordinary Portland cement (OPCC) concrete [7]. Geopolymers are novel cementitious materials that have the potential to replace conventional Portland cement composites completely, the production of geopolymer composites has a lower carbon footprint and uses less energy than the production of Portland cement [8]. Production and utilization of cement severely affect the environment due to the emission of various gases, the application of GPC plays a vital role in reducing this flaw [9]. To reduce CO_2 emissions by 55% by 2030, applying sustainable and energy-efficient materials like GPC containing Phase change materials for infrastructure development is necessary [10]. GPCs have lower CO_2 emissions than conventional concrete and Portland cement [10-13,2]. GPC is a perfect alternative to conventional cement concrete [14]. In the process of substituting OPCC concrete production, the development of GPC is considered as the major breakthrough [15]. GPC is a high-performance concrete [16]. Geopolymer or alkali-activated binders are emerging as a potential green sustainable alternative for OPCC [17]. Geopolymer composite is a new cementitious material, and it appears to be a potential replacement for conventional cement concrete [18]. Geopolymers are cementitious materials known for their environmental benefits and comparable characteristics to conventional Portland cement [19]. Compressive strength is an important property of all concrete composites, including GPC [20]. SEM analysis exhibited that the geopolymer matrix contained more dispersed small-sized pores which indicate a higher compressive strength absolutely than other experimental mixes [21]. The parameters that are identified to influence the strength gain process of GPC includes type of binder, binder to AAS ratio, alkali activators ratio, curing time, curing temperature, concentration of AAS, and Si/Al ratio in the binder material and activators [22]. the AAS to binder ratio, molarity, NaOH content, curing temperature, and ages were those parameters that have significant influences on the Compression strength of GPC incorporated with NS [23]. Increasing the molarity and Alkaline to Binder ratios results in the strength development of GPC up to a specific limit [24]. The activation of GBFS with alkaline liquids (e.g., NaOH or water glass) to produce alkali-activated GBFS cement has been studied during the past few decades [25]. GBFS has latent hydraulic properties that could be activated using suitable activators [26]. Metakaolin, fly ash, and mostly GBFS are traditionally used in the production of geopolymer [11]. in GPC, GBFS were used as binder material, along with sodium hydroxide and sodium silicate solutions as AASs [13]. Recent efforts have been made to incorporate various nanomaterials, most notably NS, into GPC to improve the composite's properties [20]. the addition of nanoparticles has a promising future for developing high-performance geopolymer composites that the construction industry can efficiently implement due to significant improvements in strength, durability, microstructure by providing additional C–S–H, N-A-S-H, and C-A-S-H gels as well as filling nano-pores in the geopolymer matrix [8]. the presence of

[1] United Nations
[2] Environmental, Social, and Governance

nanomaterials, which enhances the rate of polymerization, leads to better performance of the geopolymer [27]. The presence of NS in GPC not only has a positive effect on its physical and mechanical properties but also accelerates the geopolymer reaction, reduces the system's alkalinity, and thus, lowers the degradation of the used fibers [28]. The simultaneous evaluation of NS and steel fibers in GPC has indicated a good relationship between them [29,30]. In an investigation on the effect of POFs with different diameters and lengths in GPCs, it was revealed that the proper use of fibers increases the compressive strength and modulus of elasticity. Besides, adding fibers decreases the compressive strength [31]. In an investigation conducted on the effect of adding 0.5 of POFs to the GPCs, it was observed that the compressive resistance of the samples declined by 12-15%. The samples containing fibers with 55 mm in length had undergone lower compressive strength more than those with 48 mm in length [32,33]. The reason for the reduction in the compressive strength of specimens containing POFs can be the micro internal defects in the geopolymer matrix caused by the additional fibers [34]. Improved elastic modulus have been reported with the use of NS in GPC [35]. The impact of fiber on the long-term behavior of GPC have been highlighted [15]. The addition of different fibers also has essential potential for increasing the performances of geopolymer composites [36]. In addition to the environmental benefits of geopolymers, it possesses excellent mechanical properties, including good resistance to elevated temperatures [17]. Although a novel inorganic family of GPC is a promising building material. The need for understanding its resistance against fire at high temperatures is considered essential to ensure its long-term durability [37]. Physical examinations of the degree of cracking, spalling, brittleness, and loss of strength in GPC upon exposure to high temperatures and during fires provide an indicator of their resilience to such conditions [37]. This structure (related to the GPC) has some merits compared to the regular concrete, e.g., it provides better resistance performance at higher temperatures [38]. The concrete resistance performance against heat is complicated. When being exposed to a high temperature, GPC experiences a number of changes indicated based on their thermal ranges [39].

1. The removal of evaporative water at 100 °C
2. Calcium Silicate Hydrates hydration starts at 180 °C; as the temperature increases to 200 °C, the vapor pressure continuously elevates in the geopolymer structure.
3. The OH hydroxyl groups are evaporated at 500 °C. The dihydroxylation changes the Aluminosilicate structure, reducing the resistance level.
4. An intensely porous ceramic structure is formed at 800 °C.

increase in resistance is observed between room temperature and 200 °C and even 300 °C in research of other researchers, and various reasons are attributed to this increase. For instance, Sadighi et al. in 2012 [40] attributed this increase to the quick-drying of concrete. Similar reports are also provided [41,42]. The effect of NS on improving and reducing heat resistance can be explained as a multi-step mechanism that improves the microstructure of concrete and, consequently, increases the mechanical properties of concrete.

1- Increase in pozzolanic reaction [28]: Presence of NS in GPC increases the rate of pozzolanic reaction.

2- Filers effect of NS particles [43,44]. In the first step, the distribution of the NS particles besides other particles in concrete leads to the creation of a more compact matrix. Secondly, NS reaction in the geopolymerization process produces a greater amount of Aluminosilicate gels and reaction products from main materials.

3- Acting as a nucleus [45,46] In the structure of C-S-H gel, nanoparticles can act as a nucleus and create strong bonds with particles of C-S-H gel. In this laboratory study, increasing the mechanical properties of GBFS geopolymer concrete containing NS and POFs is one of the innovative goals. On the other hand, according to the research of others, helping the healthy environment by reducing CO_2 emissions from conventional cement production, is another goal in this research.

2. Experimental program

2.1. Materials

In this experimental study, the Portland cement type II with a 2.35 g/cm^3 of specific weight according to standard En 197-1 and the GBFS was used in powder form with the density of 2.79 g/cm^3 according to ASTM C989/C989M standard. The chemical properties of these materials are indicated in Table 1. The NS particles made up of 99.5% SiO_2 with an average diameter in the range of 15 to 25 nm were used. Crimped POFs according to ASTM D7508/D7508M standard, 30 mm in length, were also used, whose physical properties are shown in Fig. 1. The used fine aggregates (FAs) were natural clean sand with a fineness modulus of 2.95 and a density of 2.75 g/cm^3, and the coarse aggregates (CAs) were crushed gravel with a maximum size of 19 mm and a density of 2.65 g/cm^3 according to the requirements of the ASTM-C33. In this study, the GPC curing has been performed at 60 °C according to the GPC standards extracted from prestigious articles in this field.

Table1
Chemical Compositions of Materials

Component	GBFS (%)	Portland Cement Type II (%)
SiO_2 (%)	29.2	21.3
Al_2O_3 (%)	19.4	4.7
Fe_2O_3 (%)	5.8	4.3
CaO (%)	38.6	62.7
MgO (%)	2.8	2.1
SO_3 (%)	2.6	2
K_2O (%)	0.1	0.65
Na_2O (%)	0.2	0.18
TiO_2 (%)	0.6	-
Free Cao	-	1.12
LOI (%)	0.3	1.84

2.2. Mix Design

For accurate investigation, six mixture designs were considered, according to ACI 211.1-89 standard. The first sample included a regular concrete containing Portland cement where the water to cement ratio has considered to be constantly 0.45. Five other samples include GPC with different NS and POFs. The GPC samples are generally categorized into two groups: the first group lacks POFs with the NS amount of 0-8%. The second group contains 8% of NS, where the POFs are used in these designs in the form of 1 and 2 percent. In order to achieve the same performance in each mixture design and obtain a slump of about 20 ±100 mm, we have used normal polycarboxylate-based superplasticizers. Besides, 202.5 kg/m^3 of the AAS is used in this case. The used AAS is a combination of NaOH and Na_2SiO_3 with the weight ratio of 2.5, utilized with the mixture specific weight of 1483 kg/m^3 and the concentration of 12 M. The conducted studies indicate that due to the significant level of C-S-H formation when utilizing Na_2SiO_3, using a combination of NaOH and Na_2SiO_3 increases the compressive strength compared to single employment of CaOH [47]. The samples mixture design is indicated in Table 2.

Tensile Strength (N/mm^2)	>500
Length (mm)	30
Diameter (mm)	0.8
Elasticity Modulus (GPa)	>11
Bulk Density(g/cm^3)	2400

Fig. 1. Physical properties of the POFs

Table 2
Details of the mix designs (kg/m^3)

Mix ID	Cement	GBFS	Water	AAS	NS	CAs	FAs	POFs	SP
OPCC	450	0	202.5	0	0	1000	761	0	6.75
GPCNS0POF0	0	450	0	202.5	0	1000	816	0	6.75
GPCNS4POF0	0	432	0	202.5	18	1000	767	0	7.8
GPCNS8POF0	0	414	0	202.5	36	1000	718	0	8.3
GPCNS8POF1	0	432	0	202.5	36	1000	672	24	8.6
GPCNS8POF2	0	432	0	202.5	36	1000	646	48	9

2.3. Test Methods

After fabricating the samples, for better curing and increasing the resistance properties, the samples were placed in an oven at 80 °C with a thermal rate of 4.4 °C/min for 48 h. After taking them out of the oven, the samples were kept for 90 days at an ambient temperature. After curing the samples and before performing the tests heating under standard ISO834, the samples were placed in an oven at 500 °C for 1 h. In the end, by opening the oven door, the samples reached the ambient temperature [48]. In the following, the required experiments were conducted on the concrete samples, according to the related standards. In this study, the compressive strength tests were performed on 10-cm^3 cubic specimens based on BS EN 12390. Modulus of elasticity test according to ASTM C469 standard was performed on cylindrical specimens (15 cm in diameter and 30 cm in length). Weight loss test of concrete samples according to ASTM C1792-14 standard was performed on 10 cm^3 cubic samples.

3. Results and Discussion

3.1. Results of the Modulus of Elasticity Test

The results of the modulus of elasticity test of concrete samples at 20℃ and 500℃ temperature are shown in Figure 2. Figure 3 shows the concrete sample after the modulus of elasticity test. The minimum and maximum modulus of elasticity obtained from the samples of control concrete and GPC at a temperature of 500 °C belong to OPCC and GPCN8POF2 at 13.3 and 28.01 GPa, respectively, this increase in strength by approximately 1.1 times for the design. GPCNS8POF1 contains GPC compared to conventional concrete design. Increasing the fibers in GPCNS8POF1 and GPCNS8POF2 mixing designs, compared to GPCNS8POF0 GPC design, has increased the modulus of elasticity as expected. The maximum increase in modulus of elasticity belongs to the GPCNS8POF2 design, which is 38% more than the 2-GPC design. The maximum and minimum modulus of elasticity of the obtained 90-day concrete sample after heating compared to 90-day concrete samples at room temperature belong to OPCC design and GPCNS8POF1 design by 59% and 32%, respectively. It is generally reported that GPCs that are cured at high temperatures have a lower modulus of elasticity than normal concrete. For each GPC design, we see an increase in the modulus of elasticity in concrete with increasing consumption of NS and fibers. The highest and lowest percentages of reduction in modulus of elasticity of heat-treated concrete belong to OPCC and GPCNS8POF1 at 59 and 32%, respectively.

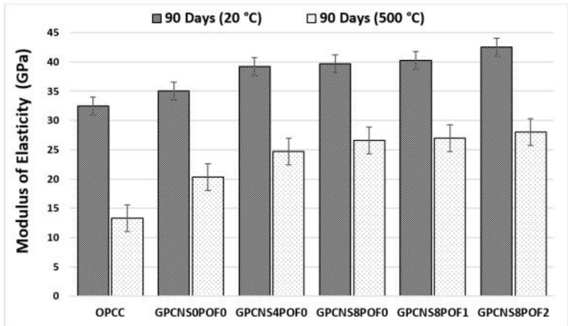

Fig. 2. The Modulus of Elasticity of the specimens

Fig. 3. Modulus of Elasticity Test

3.2. Results of the Compressive Strength Test

The results of the compressive strength test of concrete samples at 20 ℃ and 500 ℃ temperature are shown in Figure 4. Figure 5 shows the concrete sample after the compressive strength test.

The minimum and maximum compressive strengths obtained from the samples of control concrete and GPC after exposure to 500 °C belong to OPCC and GPCNS8POF0 designs of 38.89 and 75.99 MPa, respectively. GPCNS8POF0 is approximately 95% warmer than OPCC design. Increasing the fibers in

GPCNS8POF1 and GPCNS8POF2 mixing designs, compared to GPCNS8POF0 GPC design, increases the heat resistance of the sample. Has not been. The maximum and minimum compressive strength of the 90-day samples after heating compared to the 90-day concrete samples at room temperature belong to OPCC design and GPCNS8POF0 design by 37% and 8%, respectively. The percentage of reduction in compressive strength (under high temperature), the effect of the properties of the base materials (GBFS and NS) constituting the GPC in the samples of GPC are evident in the results of the diagram. In this regard, the highest and lowest percentages of reduction in compressive strength of concrete samples belong to the design of OPCC and GPCNS8POF2 by 37 and 8%, respectively.

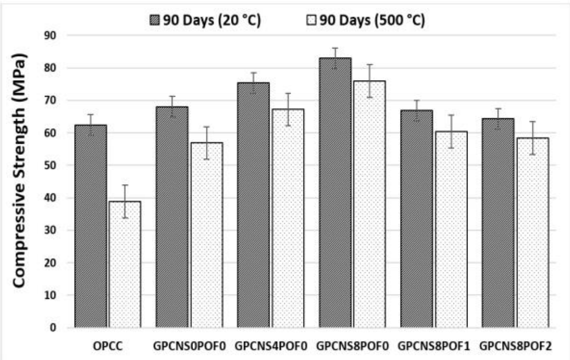

Fig. 4. The Compressive Strength of the Specimens

Fig. 5. Compressive Strength Test

3.3. Results of the weight loss test

The results of the weight loss test of concrete samples at 500 ℃ temperature are shown in Figure 6. Heat causes water to evaporate and leave the pores, cavities, interlayer and interfacial capillary spaces in the concrete structure and thus affects the weight of the concrete sample, so higher density in the cement matrix structure can be of great help. Maintain the weight of the concrete sample. The lowest weight loss for the sample before and after exposure, the GPCNS8POF0 design shows a 15% improvement in the weight loss test compared to the conventional concrete sample, but with the increase of POFs to GPC. We see severe weight loss in heat-exposed specimens. Weight loss in GPC samples containing heat-treated POFs is more severe than in conventional concrete samples, so that we see a weight loss of 0.12% for the GPCNS8POF0 design, which reached 0.073% for OPCC. The highest (0.12%) and lowest (0.064%) weight loss percentages belong to GPCNS8POF2 and GPCNS8POF0 designs, respectively. From this it can be concluded that the addition of POFs causes weight loss of concrete under heat.

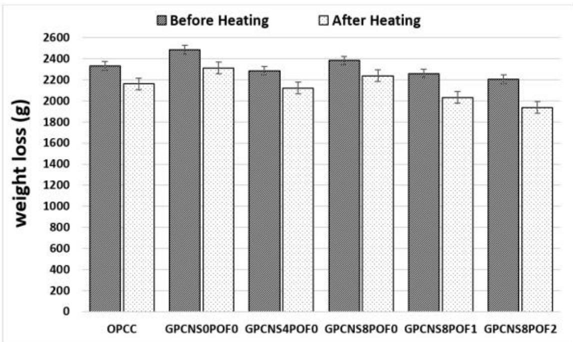

Fig. 6. The Weight Loss of the Specimens

3.4 Results of the SEM Analysis

In this study, SEM at 50 µm and 100 µ scale at 90-day curing age are shown on concrete samples at room temperature in Figure 7 and under high temperature in Figure 8. In the samples at room temperature, in the images obtained from room temperature, it can be seen that designs 2 to 6 include ferrous concrete due to the presence of GBFS and NS, compared to design 1 containing control concrete containing Portland cement of higher density and cohesion. In their microstructure, this indicates the greater participation of the particles forming ferrous concrete in the geopolymerization process compared to the Portland cement particles in the hydration process.

For ferrous concrete, by increasing the amount of NS in the designs, we see an improvement in the geopolymerization process and an increase in the production volume of hydrated gels in the concrete sample. In Portland cement, C-S-H gel consists of silicone and geopolymer groups of materials with high polymerization and Aluminosilicate structure [49]. In the sample containing NS, very few fine cracks are observed, in which NS acts as a filler to fill the spaces inside the hardened microstructure skeleton of the geopolymer paste and increase its compaction [50,51]. First, the nanoparticles fill the pores of the matrices, which reduces the porosity of the geopolymer nanocomposites, resulting in uniformity, less pores, and a more compact geopolymer matrix [28]. In fact, the pozzolanic reaction condenses and homogenizes the microstructures by converting C-H to C-S-H [52], thus creating more geopolymer gel and a denser matrix [53] However, further increase in NS content causes insufficient dispersion and accumulation of NS particles, which slightly reduces matrix density [49].

In high temperature samples, tree structure due to water evaporation and destruction of concrete microstructure is observed. In this case, cracks and cavities in the concrete microstructure are seen more than concrete samples under room temperature. For samples after exposure to high temperature, we see evaporation due to evaporation of water evaporated in the microstructure of concrete under the influence of high temperature for all designs. The amount of consumables is less. In general, it is believed that due to their ceramic-like properties, geopolymers have better performance in encountering fire compared to regular concretes [28,54,55].

GPCs resistance in encountering a significant level of heating treatment depends on its constituent chemical compounds and also the temperature and the way of curing [56]. The OH hydroxyl groups are evaporated at 500 °C. The dihydroxylation changes the Aluminosilicate structure, reducing the resistance level [57]. According to the obtained results in this investigation, all designs at room temperature have "superior" quality, and all samples at 500 °C have average and good quality [58].

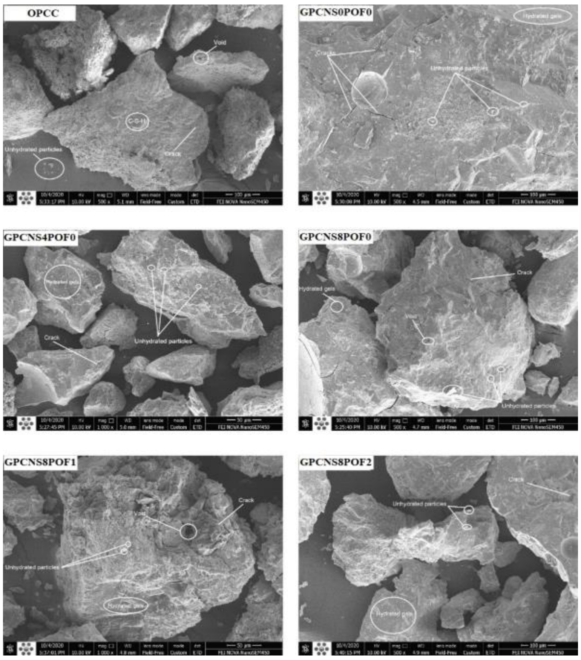

Fig. 7. SEM under room temperature

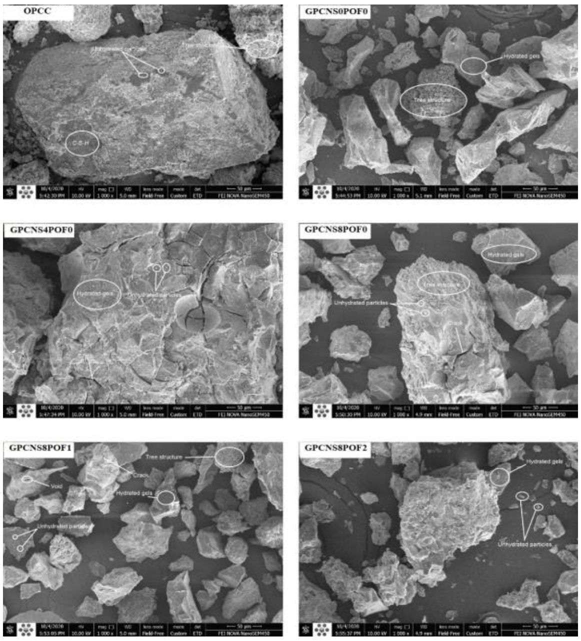

Fig. 8. SEM under high temperature

4. Conclusions

In this experimental study, tensile strength, modulus of elasticity and UPV in OPCC and GPC at 90 days of curing at 20% and 500% were investigated. The results of this research are as follows.

1. At a temperature of 20%, the lowest (32.44 GPa) and highest (42.51 GPa) modulus of elasticity belong to design concrete 1 (including OPCC) and design 6 (including GPC containing 8% NS and 2% POFs). The lowest (62.43 MPa) and the highest (82.96 MPa) compressive strength belong to Scheme 1 (including OPCC) and Scheme 4 (including GPC containing 8% NS).
2. At a temperature of 500%, the lowest (13.3 GPa) and maximum (28.01 GPa) modulus of elasticity belong to design concrete 1 (including OPCC) and design 6 (including GPC containing 8% NS and 2% POFs). The lowest (38.89 MPa) and the highest (75.99 MPa) compressive strength belong to Scheme 1 and Scheme 4 (including GPC containing 8% NS).
3. Applying high heat to GPC samples reduced the modulus of elasticity by up to 42%, compressive strength by up to 16% and reduced the weight of the samples by up to 0.12%. The effect of heat on the drop in results in control concrete is more than GPC.
4. The results of all tests at 20% and 500% showed the superiority of mechanical properties in GPC compared to OPCC.
5. SEM analysis, due to the microstructural superiority of GPC over control concrete, covered the results of other tests in this study.

Credit Authorship Contribution Statement

Mohammadhossein Mansourghanaei:
Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision.

Morteza Biklaryan:
Conceptualization, Formal analysis, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision.

Alireza Mardookhpour:
Conceptualization, Investigation, writing – original draft, Writing - review & editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abbreviations

GPC: Geopolymer Concrete
POFs: Polyolefin Fibers
GBFS: Granulated Blast Furnace Slag
NS: Nano Silica (Nano SiO_2)
OC: Ordinary Concrete
OPC: Ordinary Portland Cement
OPCC: Ordinary Portland Cement Concrete
AAS: Active Alkali Solution
SEM: Scanning Electron Microscope
C-H: Calcium-Hydrate
C-S-H: Calcium-Silicate-Hydrate (C-S-H) or Tobermorite Gel
C-A-S-H: Calcium-Aluminat- Sulfate-Hydrate (C-A-S-H) or Ettringite Gel or Tobermorite-like gel
N-A-S-H: Natrium-Aluminat- Sulfate –Hydrate (N-A-S-H) or Tobermorite-like gel
CAs: Coarse Aggregates
FAs: Fine Aggregates
SP: Super Plasticizer
NaOH: Sodium Hydroxide
Na_2SiO_3: Sodium silicate
CaOH: Calcium Hydroxide
LOI: Loss On Ignition

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