

Strengthening of fiber-reinforced geopolymer concrete after high-temperature exposure using CFRP sheets

Research Article

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Abstract: The manufacturing of Portland cement contributes to 5–8% of global CO₂ emissions. Therefore, there has been considerable emphasis on using environmentally friendly building materials. Geopolymer concrete (GPC) is an eco-friendly material, and the addition of fibers can reduce its brittleness and improve its overall performance, offering considerable potential for many structural applications. However, the structural integrity and lifespan of reinforced concrete structures are significantly diminished by fire. The current study investigates the strengthening of fiber-reinforced GPC after high-temperature exposure using carbon-fiber-reinforced polymer (CFRP) sheets. Three GPC mixes were evaluated, which included steel fibers and polyvinyl alcohol fibers with 1 vol%. Strengthening by CFRP wraps was evaluated for GPC specimens following exposure to temperatures of 25 and 500°C. This study conducts experimental testing involving a total of 36 cylinders at 28 curing days, each measuring 100 mm in diameter and 200 mm in height. The results indicate that the heated specimens exhibited a significant reduction in compressive strength up to 72.0% compared to the unheated specimens. The strengthening of heated specimens by application of CFRP wrap increased the compressive strength up to 105.2% compared to unstrengthened specimens subjected to 25°C. Therefore, the original compressive strength was restored by strengthening heated GPC specimens using CFRP wraps.

Keywords: *Compression strength • CFRP • Elevated temperature • Geopolymer concrete • Fiber-reinforced GPC • Strengthening*

1. Introduction

The construction sector has experienced a significant increase in the utilization of cement due to continued growth in urban populations [1]. There is a critical need for innovative approaches in the construction materials field, particularly ordinary Portland cement (OPC), due to established reported environmental issues. For example, the calcination of limestones and the combustion of fossil fuels generate a significant concentration of CO₂ [2]. Furthermore, calcining lime at temperatures between 1,400 and 1,500°C consumes significant resources and energy [3]. The manufacturing of OPC contributes to 5–8% of global CO₂ emissions [4]. An approximate calculation indicates that the combustion of 1 ton of carbon fuel generates around 0.4 tons of CO₂ emissions, whereas

the production of 1 ton of OPC releases about 0.55 tons of CO₂ [5]. Consequently, there is a pressing need for infrastructure to be designed with the objectives of energy efficiency and environmental protection in consideration.

Various substances, such as fly ash (FA), silica fume, rice husk ash, wood ash, and ground granulated blast furnace slag (GGBFS), etc., have contributed to addressing this issue [6]. In comparison to OPC, geopolymers offer numerous advantages, including lower energy consumption, cleaner emissions, enhanced early strength, and improved corrosion resistance [7]. Consequently, investigating the application of geopolymer concrete (GPC) sourced from industrial by-products, such as FA [8], GGBFS [9], and calcium magnesium carbonate [10], in addition to natural sources, such as metakaolin (MK) [11,12], in concrete manufacturing presents a viable approach for addressing the significant resource depletion and environmental pollution associated with conventional OPC production [13]. Most

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of the notable advancements in using GPC are the ability to decrease approximately 80% of the emissions of CO₂ [14]. GPC achieves majority of the necessary strength within 24 h due to its rapid curing properties [15]. Therefore, the environmentally friendly characteristics of the GPC make it a sustainable alternative [16]. Additionally, Provis [17] suggested the preparation of binders through the combination of silicon and aluminum with an alkaline solution, incorporating various by-products such as GGBFS and FA.

Zheng et al. [18] conducted an experimental study to evaluate the performance of fiber-reinforced geopolymer concrete (FRGPC) after exposure to variable temperatures (20–800°C). They reported that the presence of fiber led to increased compressive strength (up to 33.5%), splitting tensile strength (up to 42%), and the toughness index (up to 120.5%). Furthermore, the GPC matrix exhibits a denser structure and a stronger bond with steel fibers (SFs), resulting in a slower drop in strength compared to conventional concrete. The compressive strength of FRGPC diminishes substantially more rapidly than that of conventional concrete at temperatures over 400°C. Abdullah et al. [19] studied the performance of GPC with SF after exposure to variable temperatures (up to 750°C). The compressive strength tests revealed that GPC exhibited a strength increase of 22.3% compared to conventional concrete. Moreover, the incorporation of SFs into GPC increased its compressive strength by 61%. The findings indicate that the inclusion of SFs markedly enhances the mechanical properties of slag-based GPC, rendering it superior to OPC-based concrete.

Sitarz et al. [20] reported that the total porosity of the tested foamed geopolymers remained unaffected when subjected to heating within a temperature range of up to 1,000°C. This characteristic is regarded as advantageous for advanced materials, leading to consistent thermal insulation capabilities. The consistent porosity level across the entire range of tested temperatures guarantees stable thermal insulation properties at elevated temperatures, which is critical for fire protection. Geopolymer foams derived from coal gangue exhibit consistent mechanical properties across the tested temperature range. No sharp decline in mechanical performance was noted, and there were no occurrences of spalling or material chipping observed. The mechanical behavior exhibited is advantageous for thermal barrier applications.

On exposure to elevated temperatures, the shrinkage properties of GPC may result in microcrack formation, which will propagate further as the temperature rises [21]. GPC may experience spalling when subjected to fire scenarios due to thermal incompatibility between the aggregates and matrix, the pore pressure influence from

vapor pressure, and phase transitions [22]. Additionally, prolonged exposure, severe temperatures, and significant heating rates are essential factors contributing to the deterioration of GPC [23]. Consequently, the researchers have implemented essential measures to mitigate cracking and spalling that can arise following exposure to high temperatures. Previous studies indicate that incorporating fibers enhances the mechanical characteristics of cement-based composites by reducing the incidence of early shrinkage cracks and augmenting load-bearing capacity [24]. The resistance to elevated temperatures of GPC is effectively improved by adding fiber, typically composed of SFs and synthetic fibers such as polyvinyl alcohol (PVA) fiber and polypropylene (PP) fiber. It has been demonstrated that SF significantly enhances the mechanical properties of GPC [25]. The hooked and corrugated metal surface enhances the interaction between the matrix of GPC and fiber [26], while the SF offers supplementary mechanical anchorage throughout the debonding procedure [27]. This enhances the matrix structure, mitigating the negative effects of increased porosity due to elevated temperatures, reducing aperture size, and augmenting strength [28]. The SFs have significant ductility and can hold the incompatible displacements caused by elevated temperatures, hence mitigating thermal stress damage to the GPC matrix. Furthermore, the SFs' high thermal conductivity diminishes the temperature gradient on the specimens' exterior and interior surfaces and mitigates cracking induced by temperature differentials [18].

Zhao et al. [29] indicated that the designs of the GPC matrix, as well as the types and content of fibers, could have a significant impact on the GPC matrix's fire response. The fiber type can be categorized based on their temperature resistance functions into two primary groups: (i) fibers that exhibit lower thermal sensitivity, including steel, carbon, and basalt fibers, which provide high performance at high temperatures; and (ii) fibers characterized by low melting or decomposition points, such as natural and polymeric fibers. The first group is capable of retaining adequate residual properties throughout and following a fire, along with fiber-bridging to avert abrupt and drastic failure [30,31]. The presence of fibers led to transitioning the brittle failure to ductile damage in GPC concrete, which was effective at both ambient and elevated temperatures [32].

The uniform distribution of discrete short synthetic fibers, including PVA and PP, enhances the spalling resistance of concrete when subjected to elevated temperatures [33]. Moreover, the melting of PVA fiber occurs within the temperature ranges of 200–550°C, resulting in enlarged hole diameters within the microstructure [34]. However, cooling the residue PVA fibers after the melting

provided an additional adhesion of PVA fibers and GPC matrix, leading to increased ductility of FRGPC specimens. Nonetheless, there is a lack of research regarding the fire resistance of FRGPC.

Various strengthening techniques are available, encompassing traditional methods such as RC jacketing and steel jacketing, along with contemporary approaches like fiber-reinforced polymer (FRP). These techniques can effectively enhance the axial load and ductility capacity of structural elements. The application of carbon-fiber-reinforced polymer (CFRP) sheets as a strengthening technique for the repair and retrofitting of structural members has seen significant growth recently, attributed to its remarkable features. These include low weight, high strength and stiffness, design flexibility, ease of handling, superior resistance to corrosion, and long-term durability in adverse environmental circumstances [35]. Numerous studies have been conducted to gain in-depth comprehension of the axial response of confined concrete. CFRP sheets are particularly effective in applications involving confined concrete members [36]. Confinement denotes the technique of encasing concrete members with FRP materials, demonstrating remarkable efficacy in enhancing the structural response of these members [37]. FRP offers lateral support, limiting the material's expansion under axial loads and imparting several advantages. The intrinsic high tensile strength of FRP, particularly CFRP sheets, plays an extremely important role [38]. Concrete generally exhibits high compressive strength while being comparatively weak in tension. The application of CFRP sheets effectively mitigates this issue by greatly enhancing the tension strength of the composite system [39].

The review indicates that current research on MK–FA-based GPC matrix is limited, and the influence of different

mix design parameters (particularly when SF and PVA fibers are used in combination) on mechanical properties remains inconclusive. The literature research indicates a scarcity of studies concerning the strengthening of GPC after high-temperature exposure. A knowledge gap exists regarding the efficacy of strengthening FRGPC after high-temperature exposure using CFRP sheets. The aim of this study is to investigate the strengthening of FRGPC after high-temperature exposure using CFRP sheets. Three GPC mixes were evaluated, which included SF and PVA fibers with 1 vol%. Strengthening by CFRP wraps was evaluated for GPC specimens following exposure to temperatures of 25 and 500°C. This study conducts experimental testing involving a total of 36 cylinders at 28 curing days, each measuring 100 mm in diameter and 200 mm in height.

2. Materials and methods

2.1 Raw materials

The MK material utilized in this study was obtained from kaolinitic soil gathered from a deposit in a region in Riyadh City (Saudi Arabia) and subsequently treated for 3 h at 750°C. The FA utilized in this study, which was imported from China, was classified as Class F, according to the specifications outlined in the ASTM C618 standard [40]. Figure 1 illustrates the particle sizes of MK and FA. The chemical composition of MK is presented in Table 1. The coarse aggregate used in this study was crushed limestone with maximum particle sizes of 4.75 and 10 mm. The fine aggregate was a white sand with a maximum particle size of 2 mm. The GPC composite underwent activation

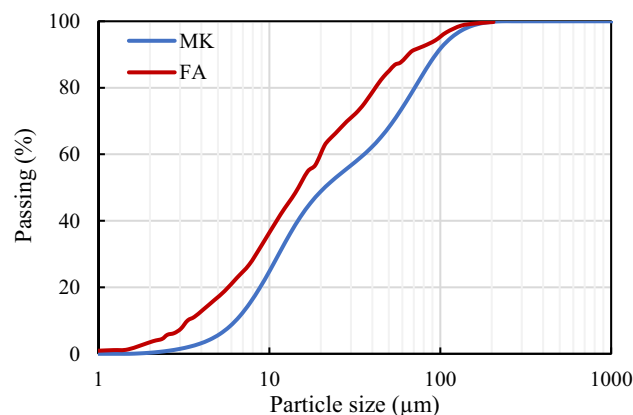


Figure 1. The MK and FA particle sizes used in this study [42].

Composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	CaO	SO ₃	K ₂ O	Na ₂ O	MgO	P ₂ O ₅	Others
Value (%)	50.995	42.631	2.114	1.713	1.287	0.439	0.337	0.284	0.127	0.051	0.022

Table 1. MK's chemical analysis [42].

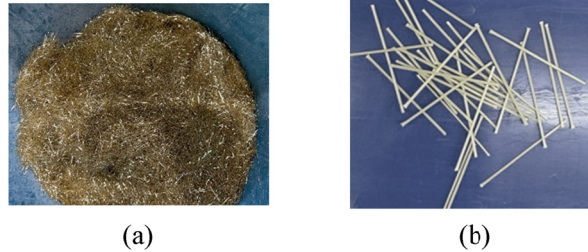


Figure 2. Fiber types used in this study: (a) SF and (b) PVA.

through a sodium-based activator that included a sodium silicate solution (Na₂SiO₃) alongside a sodium hydroxide solution (NaOH). The 14 M NaOH solution was prepared 1 day before the specimen was prepared. The Na₂SiO₃ solution possessed a 3.3 ratio of SiO₂ to Na₂O. The FRGPC mix incorporated two varieties of fibers, including straight SF and straight PVA fiber. The fiber composition consisted of 1 vol% in the two mixes: the first mix with 1% for SF and the second with 1% for PP. The SF features an aspect ratio of 100, measuring 20 mm in length and 0.2 mm in diameter. The straight PVA fibers exhibit an aspect ratio of 45, measuring 30 mm in length and 0.66 mm in diameter. The tensile strengths of the SF and PVA fibers were measured at 1,225 and 900 MPa (given by the manufacturer), respectively. The modulus of elasticity of the SF and PVA fibers were measured at 200 and 23 GPa (given by the manufacturer), respectively. Figure 2 displays the two fiber types (PVA and SF) utilized in the study. The CFRP

utilized in this investigation consists of a unidirectional carbon fiber fabric that is usually employed in strengthening applications of RC structures. It was manufactured by Horse Company in China. As recommended by the manufacturer, Sikadur-300 epoxy adhesive resin was utilized. The characteristics of the CFRP sheet and Sikadur-300 are provided in Table 2. The CFRP sheet's tensile strength was assessed by tensile tests on standard coupons following the ASTM D3039 guidelines [41].

2.2 FRGPC mix proportions

The test GPC matrix for this program was developed using a reference mix determined from a series of iterative laboratory trials conducted by the authors, aimed at achieving a mix design that combines high compressive strength with satisfactory workability. The experimental testing program comprised three FRGPC mixes. The initial mix served as a control mixture (FRGPC0) and was fabricated without fibers. The second mix (FRGPC1) was fabricated with 1% by volume SFs, while the third mix (FRGPC2) had 1% by volume PVA fibers. The proportions for the various mixes are shown in Table 3.

2.3 Specimen preparation

MK, FA, and aggregates (coarse and fine) underwent a dry mixing process for a period of 2 min. The dry mix constituents were combined with the mixed alkaline solutions (Na₂SiO₃ and NaOH). The mixing procedure persisted for a few minutes until the mix achieved a homogeneous condition. For the FRGPC1 and FRGPC2 mixes, SF and PVA

Material	Property	Value	Notes
Epoxy adhesive	Tensile strength	71.5 MPa	Given by the manufacturer
	Tensile elastic modulus	1.86 GPa	
	Tensile strain at break	5.25%	
CFRP sheet	Thickness	0.6 mm	Experimental values
	Ultimate tensile strength	1,122 MPa	
	Tensile elastic modulus	68.9 GPa	

Table 2. CFRP sheet and epoxy adhesive characteristics.

Material		FRGPC0 mix	FRGPC1 mix	FRGPC2 mix
	MK	285	285	285
	FA	65	65	65
	White sand (max size: 2 mm)	419	419	419
	SF	—	78.5	—
	PVA	—	—	13
Alkaline solutions	Na ₂ SiO ₃	197	197	197
	NaOH	110	110	110
Coarse aggregate	(Maximum size of 10 mm)	1,272	1,272	1,272
	(Maximum size of 4.75 mm)	180	180	180

Table 3. FRGPC mix proportions in kg/m³.



Figure 3. GPC specimens after casting in molds.

fibers were integrated into the mixes, and the mixing procedure continued for an approximate duration of 4 min. The FRGPC was gradually cast into the specimens' molds to reduce the potential for separation, and a vibrating table was employed to mitigate void creation. Figure 3 depicts the GPC specimens after casting in molds. The specimens underwent a curing process lasting 28 days in a controlled laboratory environment, maintained at a relative humidity of $20 \pm 2\%$ and an ambient temperature of $24 \pm 2^\circ\text{C}$. The test matrix employed in this study is illustrated in Table 4. The abbreviations “GPC0,” “GPCS,” and “GPCP” signify the FRGPC mixes: GPC0 indicates the control mix without fibers; GPCS and GPCP refer to the mixes containing SF and PVA fiber, respectively. In the specimen identifiers, alphanumeric characters were involved. The first string denotes the mix type that was employed. The specimens that were subjected to temperatures of 25 and 500°C are denoted by the designations “25” and “500,” respectively. The “S” signifies the specimens with CFRP strengthening. Each parameter was tested using three replicates to ensure consistency and increase confidence in the study's

conclusions. This study employed 36 cylinders, each measuring 100 mm in diameter and 200 mm in height.

2.4 CFRP strengthening

The GPC specimens were strengthened with CFRP sheets, employing a single layer that featured a 100 mm overlap. Before the application of the CFRP sheet, the surface of specimens was roughened via sandblasting. This was conducted to create a strong adhesion for the CFRP layer. Initially, the surface of the specimen was thoroughly cleaned to remove any impurities, such as dust particles. The subsequent procedure entailed the application of an epoxy primer coating to the surface of the concrete to fill any air voids and guarantee strong adherence. A thin layer of epoxy was subsequently applied to the specimens. Then, the CFRP sheet was carefully wrapped around the specimens. A roller was utilized to release the entrapped air and enhance the impregnation process. Strict protocols were applied to ensure that no air voids were present.

Concrete mix	Specimen ID	Fiber type	Exposure to temperature (°C)	Strengthening	No. of specimens	
FRGPC0	GPC0-25	—	25	—	3	
	GPC0-500		500		3	
	GPC0-S-25		25		CFRP	3
	GPC0-S-500		500		3	
FRGPC1	GPCS-25	SF	25	—	3	
	GPCS-500		500		3	
	GPCS-S-25		25		CFRP	3
	GPCS-S-500		500		3	
FRGPC2	GPCP-25	PVA	25	—	3	
	GPCP-500		500		3	
	GPCP-S-25		25		CFRP	3
	GPCP-S-500		500		3	
	Total no. of specimens				36	

Table 4. Test specimens.



Figure 4. GPC specimens after casting in molds.

Figure 4 illustrates the strengthened specimens with CFRP sheets.

2.5 Testing method

2.5.1 Heating of concrete specimen process

An electric oven was used to heat the GPC specimens until they reached the specified temperature of 500°C. The heating of GPC specimens was implemented in the oven by increasing the temperature with an average rate of 8°C/min until they attained 500°C. The heating of GPC specimens persisted for 3 h, then the oven was turned off. Subsequently, the FRGPC specimens were permitted to cool until they reached the ambient temperature for 24 h prior to testing. Figure 5 illustrates the time-temperature curves employed in this work for exposures at 500°C.

2.5.2 Compressive strength test

The GPC specimens in this study were subjected to uniaxial compressive pressure. The specimen's top surface was sealed with sulfur to ensure complete leveling during compression testing. A compressometer was attached to each specimen to assess the axial strain throughout the test, as illustrated in Figure 6. The compressometer featured two linear variable differential transformers (LVDTs) positioned on circular sleeves encircling the specimen. Pin-type support was employed to secure the sleeves to the specimen in order to prevent their impact on the dilation of the specimens. The measurements were recorded during the investigation by connecting the wires of the LVDTs to a data acquisition system. The specimens were subjected to uniaxial compression until failure occurred. The compressive strength of the concrete was assessed following the process specified in ASTM C39 [43].

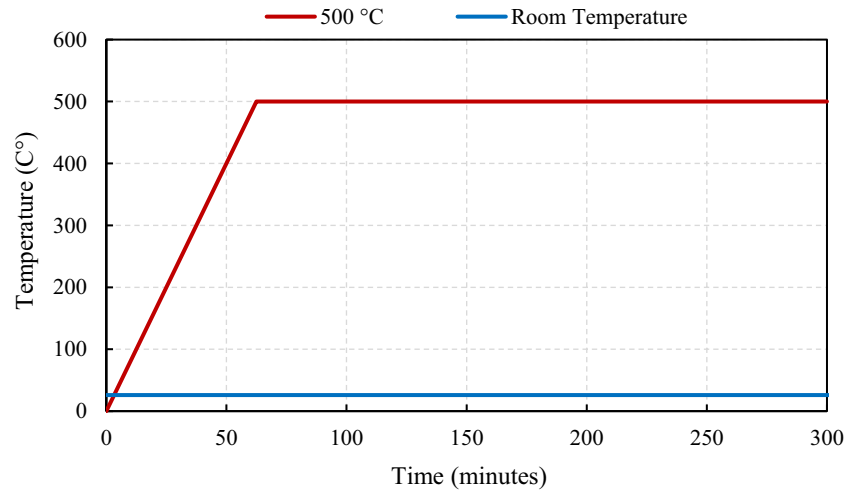


Figure 5. The heating curve used in the current study.



Figure 6. Test setup.

3. Results and discussion

3.1 Failure modes

The failure modes of all specimens following the compressive test are illustrated in Figure 7. Generally, the ultimate failure mode of the GPC specimens was substantially influenced by the inclusion of fibers, heat exposure, and CFRP wrap. All GPC cylinders displayed vertical cracks, as illustrated in Figure 7. The tested GPC cylinders exhibited increased cracking and crushing when exposed to a temperature of 500°C, as illustrated in Figure 7. Minor thermal cracks were observed on the GPC cylinders' surfaces with exposure to a temperature of 500°C. Moreover, Albidah et al. [34,44] reported that there were no significant cracks

when subjected to increased temperatures of up to 600°C, which shows the results of this study are consistent with previous studies. Generally, at the high temperature (500°C), the vertical cracks on the cylinder sides were nearly identical in position to those observed at 25°C, accompanied by numerous tiny microcracks around the fractures. In addition, all the heated specimens exhibited noticeable peeling at the middle and upper surfaces. During the test, numerous cracks were discovered, originating and intersecting one another, and the matrix's brittle attributes were evident. The matrix's dryness and shrinkage at elevated temperatures facilitated the propagation of cracks along vulnerable regions, eventually leading to damage. The unstrengthened GPC cylinders exposed to ambient temperatures exhibited more tendency for brittle failures. In contrast, the unstrengthened GPC cylinders exhibited a reduced propensity for brittle failure, demonstrating increased ductility when subjected to elevated temperatures of 500°C.

The GPC specimens, without fibers, experienced brittle failure mode with more cracking and concrete crushing, as illustrated in Figure 7. When subjected to increased temperatures, the GPC0-500 specimens (without fibers) demonstrated a reduced tendency for brittle failure. The concrete cover displayed early signs of spalling. As a result, a gradual failure was observed when the applied load started to diminish, unlike the same type of specimens (GPC0-25) that were tested at an ambient temperature. Significant fracture was observed in GPC0-500 specimens as the temperature increased, marked by prominent fragmented cracks that remained partially attached.

The GPCS-25 and GPCP-25 specimens exhibited distinct patterns, where the fibers markedly reduced crack



GPC0-25



GPCS-25



GPCP-25



GPC0-500



GPCS-500



GPCP-500



GPC0-S-25



GPCS-S-25



GPCP-S-25



GPC0-S-500



GPCS-S-500



GPCP-S-500

Figure 7. Failure modes of all GPC specimens.

development. At the failure, the GPCS-25 and GPCP-25 specimens exhibited diminished crack widths compared to the GPC0-25 specimen, as illustrated in Figure 7. Despite some portions of concrete being fractured, those portions were still attached to specimens, indicating that the fibers (SF and PVA) provided a protective role against cracks even after exposure to high temperatures. Elsanadedy et al. [45] and Alharbi et al. [42] found that the use of SF and hybrid fibers (SF + PVA) in the GPC mix enhanced crack bridging. These results are consistent with the results of the present investigation. After elevated temperatures, the FRGPC specimens (GPCS-500 and GPCP-500) exhibited considerable delamination on the middle height of specimens, signifying a reduced adhesion strength between the GPC matrix and fibers (i.e., SF and PVA). The incorporation of fibers altered the failure pattern of GPC specimens from brittle to ductile by improving the mix's toughness, consistent with prior research on cement concrete [46,47]. The failure behavior of heated FRGPC specimens demonstrated an increase in ductility. The improved ductility can be ascribed to the presence of the fibers, which mitigated crack development and expansion while preserving load resistance across bridging the cracks.

All the strengthened specimens failed due to the concrete crushing and the rupture of the CFRP wrap caused by hoop tension. The separation of the CFRP wrap from the surface of the strengthened specimens is associated with the ringed rupture of the CFRP, as illustrated in Figure 7. The implementation of CFRP wrap delayed the development of cracks by confining the specimen. However, with increasing load, the concrete expanded laterally, and hence the CFRP wrap started to elongate and deform gradually. After the maximum load, the extent of core compression and exterior protrusion intensified, leading to CFRP wrap rupturing. This immediately decreases in strength and consequently causes a sudden collapse of the specimens. The strengthened specimens collapsed abruptly and explosively, accompanied only by snapping sounds. Nevertheless, the CFRP wrap provides a superior constraining effect on the GPC specimens' core post-peak load, leading to enhanced specimen integrity. Furthermore, the strengthened specimens exhibited a higher degree of ductility than the unstrengthened specimens when they were exposed to the same temperatures. The rupture of the CFRP wrap for the specimen without fibers (i.e., GPC0-S-25 and GPC0-S-500 cylinders) occurred at the mid-height region of the cylinder, which extended to the top surface. The specimen with fibers (i.e., SF and PVA fibers) exhibited a ruptured CFRP wrap at the top surface of cylinders and extended to the mid-height reign. The abrupt and explosive characteristics of the

failure illustrate the discharge of an exceptional quantity of energy due to the uniform restricting force exerted by the CFRP wrap. The analysis of the fractured cylinders revealed effective adhesion between the concrete and the CFRP wrap, showing that no debonding occurred at any point during the loading procedure, as illustrated in Figure 7. The strengthened specimens, comprising both unheated (GPC0-S-25, GPCS-S-25, and GPCP-S-25) and heated (GPC0-S-500, GPCS-S-500, and GPCP-S-500) specimens, underwent similar failure mechanisms. The CFRP wrap has predominantly failed due to the vertical and horizontal ruptures in strengthened specimens, whether they were unheated or heated.

3.2 Compressive strength

Figure 8 and Table 5 illustrate the average value of the three cylinders for each mix under the compressive strength testing. The control GPC specimens (GPC0-25) at 25°C exhibited a compressive strength of 46.0 MPa at 28 days curing time. The incorporation of SF fiber (i.e., GPCS-25 specimens) exhibited a compressive strength of 47.2 MPa with a modest increase of 2.5% relative to the GPC0-25 specimens. On the contrary, the incorporation of PVA fiber (i.e., GPCP-25 specimens) exhibited a compressive strength of 36.0 MPa with a decrease of 21.8 and 23.7% relative to the GPC0-25 and GPCS-25 specimens, respectively. Previous studies demonstrated that the inclusion of SF in concrete [47] and GPC mixes [12] results in marginally augmented compressive strength; however, it markedly enhances ductility. Thomas and Ramaswamy [48] reported that the compressive strength increased as a result of adding hooked-end SF fibers less than 10%. These results are consistent with the findings of the present investigation. Zheng et al. [18] conducted an experimental study to evaluate the performance of FRGPC after exposure to variable temperatures (20–800°C). They reported that the presence of fiber led to increased compressive strength (up to 33.5%), splitting tensile strength (up to 42%), and the toughness index (up to 120.5%). Furthermore, the GPC matrix exhibits a denser structure and a stronger bond with SFs, resulting in a slower drop in strength compared to conventional concrete. The compressive strength of FRGPC diminishes substantially more rapidly than that of conventional concrete at temperatures over 400°C. Abdullah et al. [19] studied the performance of GPC with SF after exposure to variable temperatures (up to 750°C). The compressive strength tests revealed that GPC exhibited a strength increase of 22.3% compared to conventional concrete. Moreover, the

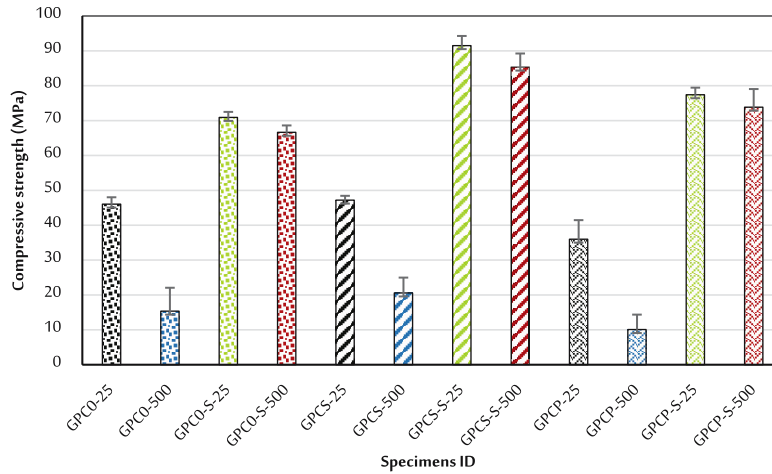


Figure 8. Compressive strength of all GPC specimens.

Specimens	Compressive strength (MPa)	Relative difference*	Modulus of elasticity (MPa)	Relative difference*
GPC0-25	46.0	—	22666.4	—
GPC0-500	15.4	−66.7%	2338.7	−89.7%
GPC0-S-25	70.9	+54.0%	30930.2	+36.5%
GPC0-S-500	66.6	+44.7%	4867.7	−78.5%
GPCS-25	47.2	—	20649.6	—
GPCS-500	20.6	−56.4%	1523.2	−92.6%
GPCS-S-25	91.5	+93.9%	21794.9	+5.5%
GPCS-S-500	85.3	+80.9%	3225.4	−84.4%
GPCP-25	36.0	—	17764.6	—
GPCP-500	10.1	−72.0%	1328.2	−92.5%
GPCP-S-25	77.4	+115.1%	19710.1	+11.0%
GPCP-S-500	73.9	+105.2%	3273.8	−81.6%

*Compared to the control sample in each mix.

Table 5. Summary of test results.

incorporation of SFs into GPC increased its compressive strength by 61%. The improvement in the compressive strength can be ascribed to the bonding effect between the SFs and concrete matrix, which mitigates crack expansion and development while sustaining load capacity at the cracks [49]. Other studies have indicated that PVA fibers demonstrate an adverse influence on the compressive strength [50,51], with some instances showing a minimal increased impact [52,53]. Consequently, the finding of this study is consistent with earlier findings. This discrepancy is due to the fact that PVA fiber has different lengths and configurations [54].

Figure 8 illustrates the variation in compressive strength after exposure to 500°C compared to ambient temperature.

The heated specimens exhibited a significant reduction in compressive strength by 66.7, 56.4, and 72.0% for GPC0-500, GPCS-500, and GPCP-500, respectively, when compared to the unheated specimens GPC0-25, GPCS-25, and GPCP-25. This drop in strength after exposure is because the aggregates and the GPC matrix expand at different rates when heated. This causes cracks and weakens the bond between the aggregates and the GPC matrix [55]. Additionally, the water in the GPC matrix migrates to the heated specimens' exterior surface and evaporates when exposed to high temperatures. This mechanism primarily occurs within the temperature range between 100 and 300°C, and water evaporation diminishes beyond this range [56]. Furthermore, this mechanism results in the

deterioration of the interior microstructure and a decrease in compressive strength [56]. According to Albidah et al. [44], the scanning electron microscopy (SEM) analysis revealed that the micrographs taken for a GPC sample after heating at 400°C showed a sponge-like structure with significant porosity, which led to a decrease in compressive strength.

The strengthened specimens exhibited compressive strength increase of 54.0, 93.9, and 115.1% for GPC0-S-25, GPCS-S-25, and GPCP-S-25, respectively, in comparison to the unstrengthened specimens GPC0-25, GPCS-25, and GPCP-25 at ambient temperature (25°C). The same trend was observed in the strengthened heated specimens that were subjected to a 500°C temperature, where the compressive strength significantly increased by 334, 314.8, and 632.4% for GPC0-S-500, GPCS-S-500, and GPCP-S-500, respectively, in comparison to the unstrengthened specimens GPC0-500, GPCS-500, and GPCP-500. Abadel [12] investigated the compressive behavior of GPC containing reclaimed asphalt aggregate. It is found that the application of CFRP wraps markedly enhanced compressive strengths, with ratios varying from 87.7 to 368.8% for unheated specimens and 58.8–153.9% for heated specimens (300°C), in comparison to the unstrengthened control specimen of each mix. The results indicated that the CFRP wrap positively affected the confinement of the GPC core. Upon surpassing the maximum load, the GPC underwent expansion due to uniaxial compression, enhancing the interaction between the GPC and CFRP wrap, resulting in increased compressive strength. Nonetheless, exposure to high temperatures influences the compressive strength of the GPC and FRGPC mixes. Enhancing the strength of GPC and FRGPC mixes is crucial for achieving the required strength, accomplished in this work with the application of CFRP wraps.

3.3 Stress–strain curves

Figure 9(a) illustrates the stress–strain curves for all specimens. The unheated specimens had a uniform linear increase in stress throughout the initial loading phase. During the elastic phase, the strains were rather minor, as illustrated in Figure 9(b) and (d). A similar pattern was seen in the heated specimens, which demonstrated greater strains than the unheated ones at the same stress level, as illustrated in Figure 9(c) and (e). The strains gradually achieved their maximum limit as the load increased. The curves began to exhibit a nonlinear pattern as the stresses approached their maximum values. Subsequently, the slope of the curve began to decrease, and nearly all strain measurements exceeded the yield strain values. Before

failure, GPC cylinders exhibited a notable reduction in stress. The heated GPC mixes showed reduced stiffness. This reduction mirrored the pattern observed for compressive strength. The slope of the curve diminished as the temperature increased from 25 to 500°C, as illustrated in Figure 9. These curves illustrate that the initial stiffness of both the GPC mixes, with and without fibers, experience a more pronounced reduction in initial stiffness when subjected to a temperature of 500°C. This decline resulting from exposure to 500°C can be attributed to inadequate bonding between the GPC matrix and aggregate, as well as a decrease in moisture content.

The curves indicate that CFRP confinement effectively enhances the strength of the GPC core and improves the specimens' overall strength. Figure 9 and Table 5 illustrate that the strengthened FRGPC specimens with SF, whether heated or unheated, exhibit the highest maximum stresses among all specimens. This indicates that the CFRP wraps effectively enhanced the heated and unheated specimens' resistance by demonstrating increased confinement energy until they reached the CFRP rupture stresses. The contribution of CFRP confining was particularly evident in the evaluation of the enhancement in ultimate strains. The ultimate strains at ultimate stress for the FRGPC specimens exhibited a substantial increase of four times in comparison to those for the unstrengthened specimens. The strengthened specimens exhibited markedly enhanced performance in ultimate strain compared to the unstrengthened specimens [57]. The strengthened specimens subjected to elevated temperatures (500°C) exhibited approximately linear stress–strain curves until reaching maximum stress, followed by a rapid decline in compressive stress. Furthermore, the strengthened FRGPC specimens exhibited an enhanced capacity for energy absorption (quantified by the area under the curve) in comparison to the unstrengthened specimens. Previous research has reported a comparable observation [58].

The strain at maximum stress increased as the temperature was raised from 25 to 500°C. For unstrengthened specimens at ambient temperature, the strain at maximum stress was measured between 0.0026 and 0.0091. For heated specimens, the range was substantially greater, ranging from 0.0084 to 0.0109. Regarding the strengthened specimens, the unheated specimens showed strain at maximum stress between 0.0098 and 0.0268, while they were between 0.0151 and 0.0396 for heated specimens. At 25°C, for the FRGPC specimens, the strain at maximum stress increases by 243.7 and 39.0% for SF and PVA fibers, compared with GPC specimens. In addition, the strengthened FRGPC specimens show the same trend with an increased ratio of 173.7 and 88.3% for SF and PVA fibers, compared

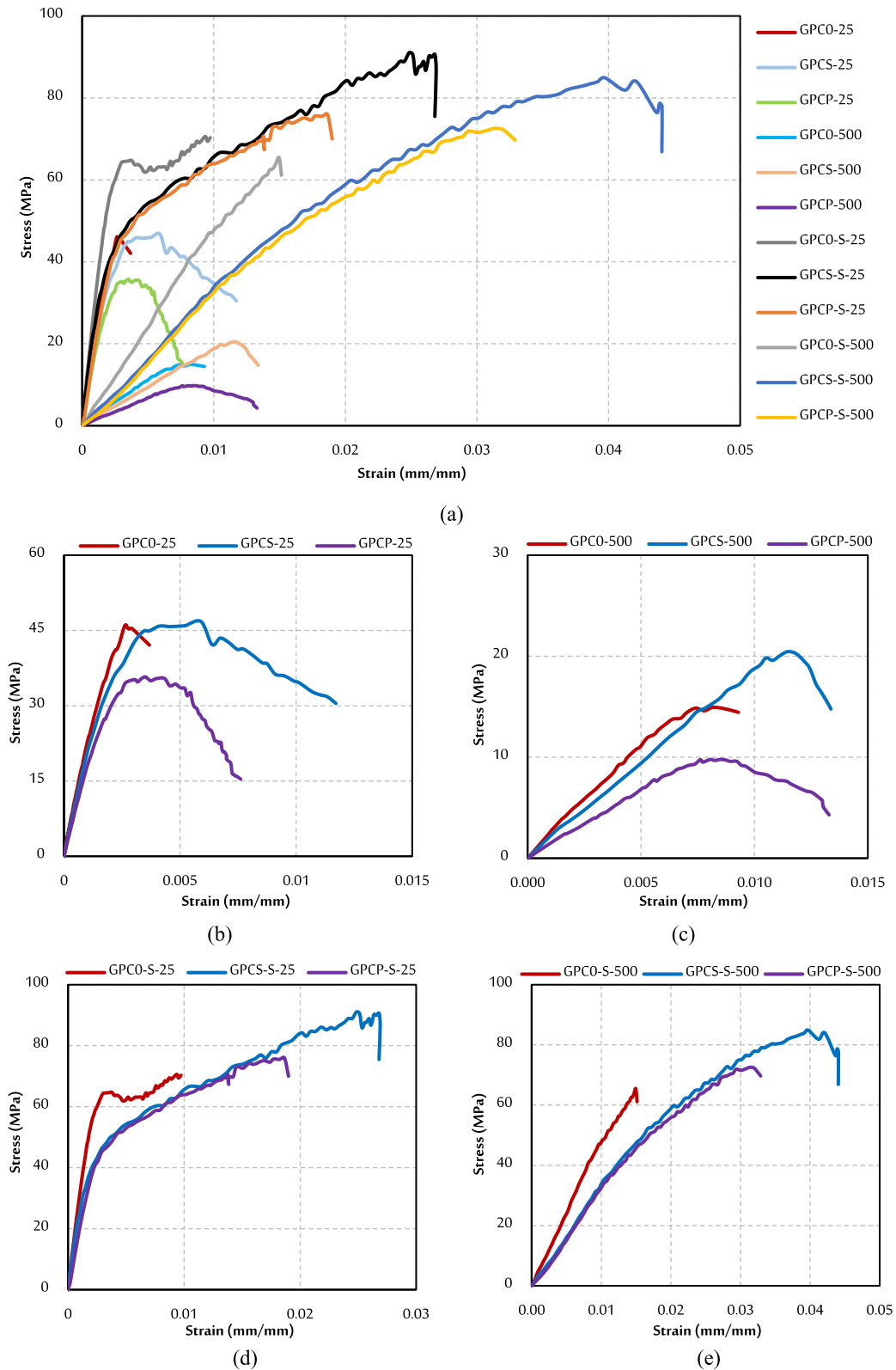


Figure 9. Stress-strain curves: (a) All specimens; (b) unstrengthened specimens exposed to 25°C; (c) unstrengthened specimens exposed to 500°C; (d) strengthened specimens exposed to 25°C; and (e) strengthened specimens exposed to 500°C.

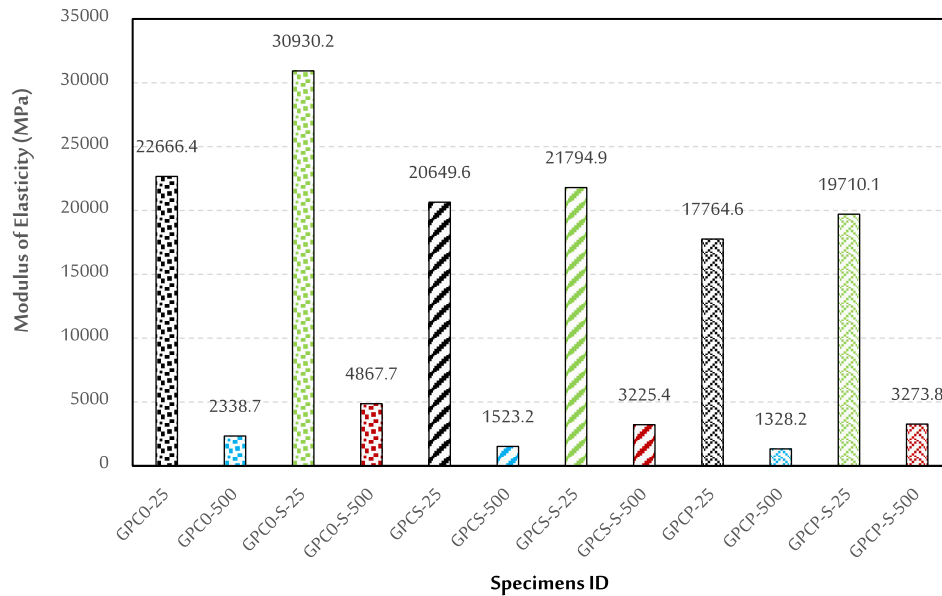


Figure 10. Modulus of elasticity of all GPC specimens.

with unstrengthened GPC specimens. The same pattern was seen when the specimens were exposed to 500°C. Fibers caused the strain at maximum stress to rise by 26.5% for the strengthened specimens and 161.8% for the unstrengthened specimens. Upon exposure to elevated temperatures, the GPC matrix structure becomes porous and less compact. The adhesion with fibers diminishes, and the synergistic effect of composite materials declines, leading to an escalation in strain at maximum stress. However, while the bond between fibers and the matrix diminishes, the fibers continue to mitigate crack development, hence reducing the likelihood of attaining maximum stress and enhancing maximum strain [18].

3.4 Effectiveness of fiber types

The effectiveness of fiber types was evaluated through the compressive strength after exposure to different temperatures (25 and 500°C). Table 5 displays the compressive strength of all tested specimens. This shows the residual compressive strength of GPC mixes after exposure to high temperatures relative to their strength at ambient temperature (25°C). The results indicated that the inclusion of SFs in the FRGPC specimens positively influences compressive strength, while the PVA fiber had adverse influences compared to GPC specimens. The incorporation of SF (i.e., GPCS-25 specimens) exhibited a slight increase of 2.5% relative to the GPC0-25 specimens. On the contrary,

the incorporation of PVA fiber (i.e., GPCP-25 specimens) exhibited a decrease of 21.8 and 23.7% relative to the GPC0-25 and GPCS-25 specimens, respectively. The inclusion of SF mitigated the decline in compressive strength after exposure to elevated temperatures (500°C) relative to GPC0-500 (without fibers). GPCS-500 specimens demonstrated reduction ratios of 56.4% while it was 66.7% for the GPC0-500 specimens; on the contrary, the GPCP-500 specimens (with PVA fiber) had reduction ratios of 72.0% after being exposed to 500°C.

The deterioration rate decreased with the incorporation of SF, while it increased with the incorporation of PVA fibers. The randomly distributed SFs in the FRGPC specimens create a specific skeleton within the GPC matrix that can mitigate the further propagation of micro-cracks. This enhances the matrix structure, mitigating the negative effects of increased porosity due to elevated temperatures, reducing aperture size, and augmenting strength [28,59]. The SFs have significant ductility and can hold the incompatible displacements caused by elevated temperatures, hence mitigating thermal stress damage to the GPC matrix. Furthermore, the SFs' high thermal conductivity diminishes the temperature gradient on the specimens' exterior and interior surfaces and mitigates cracking induced by temperature differentials [18]. The melting of PVA fiber occurs within the temperature ranges of 200–550°C, resulting in enlarged hole diameters within the microstructure [34,60]. The melting process adversely affects the FRGPC mix's properties, resulting in a marked reduction in compressive

strength compared to GPC specimens with and without SFs. However, cooling the residue PVA fibers after the melting provided an additional adhesion of PVA fibers and GPC matrix, leading to increased ductility of FRGPC specimens compared with GPC specimens. The fibers' influence on the post-peak behavior of the curves was greater than that of the control mix, despite the exposure to temperatures of 500°C, as demonstrated in Figure 9. Despite PVA fibers having a lower modulus of elasticity than SFs, they can effectively bridge microcracks, as evidenced by increased ductility compared to control specimens and also by prior research [61].

3.5 Effectiveness of CFRP strengthening

The effectiveness of strengthening the heated GPC specimens using CFRP sheets has been observed in the stress-strain response. The compressive strength was substantially enhanced by the application of CFRP wraps, which provided significant confinement for the GPC core. The ductility and strength of GPC specimens were substantially enhanced after exposure to different temperatures (25 and 500°C), as shown in Figure 9. Figure 9 illustrates the influence of the CFRP wraps on the stress-strain curves of all GPC specimens, both at ambient and elevated temperatures. This indicates a significant improvement in the strength and ductility of all mixes, particularly evident in specimens subjected to 500°C. The effectiveness of CFRP confinement improved with the inclusion of fibers. For unheated strengthened specimens, the compressive strength increased by 54.0, 93.9, and 115.1% for GPC0-S-25, GPCS-S-25, and GPCP-S-25, respectively, compared with GPC0-25, GPCS-25, and GPCP-25 specimens. The interfacial transition zone is crucial in influencing the behavior of concrete due to the significant volume filled by coarse aggregate [62,63]. In addition, the thermal incompatibility between the GPC matrix and aggregate directly affects the reduction in concrete strength when subjected to elevated temperatures [64]. Moreover, the heated strengthened specimens show the same trend with increased ratios of 334.0, 314.8, and 632.44% for GPC0-S-500, GPCS-S-500, and GPCP-S-500, respectively, compared with GPC0-500, GPCS-500, and GPCP-500 specimens.

The strengthening of heated specimens (i.e., those exposed to 500°C) by application of CFRP wrap resulted in increase in compressive strength of 44.7, 80.9, and 105.2% for the GPC0-S-500, GPCS-S-500, and GPCP-S-500 specimens, respectively, when compared to those for the unheated specimens (i.e., those subjected to 25°C) GPC0-25, GPCS-25, and GPCP-25. Therefore, the original compressive

strength (exposure to 25°C) was restored by strengthening heated GPC specimens (exposure to 500°C) using CFRP wraps. This illustrates the effectiveness of the CFRP strengthening technique, especially for the heated specimens. These observations align with previous investigations [57,65]. The strengthening of heated specimens using CFRP sheets proved more effective in retrofitting the compressive strength of GPC and FRGPC specimens. Furthermore, although exposure to 500°C led to decreased compressive strength by up to 72%, there was no significant reduction in the compressive strength after strengthening of unheated or heated specimens. The reduction ratios were 6.0, 6.7, and 4.6% for GPC0-S-500, GPCS-S-500, and GPCP-S-500, respectively, compared with GPC0-S-25, GPCS-S-25, and GPCP-S-25 specimens. Although the inclusion of PVA fiber in unstrengthened specimens had a negative impact on control GPC specimens, the strengthening of FRGPC specimens with PVA fiber resulted in an increase of 9.2 and 10.8% when exposed to 25 and 500°C, respectively, compared to strengthened GPC specimens at the same temperature exposure. According to Bisby et al. [65], FRP confinement enhances compressive strength at elevated damage degrees. This indicates that the enhancement of concrete strength is contingent upon both unconfined compressive strength and the intrinsic physical properties of the concrete mix. The parameters of the concrete mix influence the failure strength at the ultimate limit state, which may exhibit characteristics similar to granular material. This results in shear failure, which is a common occurrence in soils and granular solids. Furthermore, for all GPC specimens (both with and without fibers), the ultimate strain results of strengthened specimens exhibited an increase after exposure to evaluated temperatures compared to those of unheated strengthened specimens.

3.6 Modulus of elasticity after high temperatures

The modulus of elasticity can be referred to as the secant stiffness value corresponding to 40% of the maximum compressive strength in the ascending segment of the stress-strain curve. Figure 10 and Table 5 demonstrates that irrespective of the presence of fibers or CFRP wrap, the modulus of elasticity decreases as the temperature rises from 25 to 500°C. At 500°C, the modulus of elasticity for the unstrengthened specimens ranges from 1328.2 to 2338.7 MPa, constituting 7.4–10.3% of the value at ambient temperature. Moreover, the modulus of elasticity for the strengthened specimens ranges from 3225.4 to 4867.7 MPa, constituting 14.8–16.6% of the value at ambient

temperature. The original compressive strength (exposure to 25°C) can be restored by strengthening heated GPC specimens (exposure to 500°C) using CFRP wraps; however, the modulus of elasticity remains unrecoverable due to the confinement effect being inadequate for restoring the modulus of elasticity of heated GPC specimens. The incorporation of fibers (SF and PVA) negatively influences the modulus of elasticity, with a total decrease of 8.9 and 21.6% for the GPCS-25 and GPCP-25 specimens, respectively, compared with GPC0-25 specimens. The same trend was noticed at elevated temperatures with decreases of 34.9 and 43.2% for the GPCS-500 and GPCP-500 specimens, respectively, compared with GPC0-25 specimens. This is due to the fibers potentially not fulfilling their complete function during the elastic phase. As temperature rises, internal loss of moisture induces structural alterations, and the temperature discrepancy between external and internal surfaces generates thermal stress, hence diminishing the GPC specimens' performance [18]. The aggregate undergoes expansion and deformation, resulting in considerable displacement incompatibility with the GPC matrix, which leads to a substantial reduction in strength. The reduction in modulus of elasticity is considerably greater than the effect of temperature on compressive strength, which was aligned with the previous studies [12,18]. The internal structure of the GPC matrix has been damaged due to exposure to high temperature, resulting in diminished strength and significantly increased compressive deformation under the same stress [66]. However, the results demonstrate that the strengthening of GPC specimens positively affects their modulus of elasticity. The modulus of elasticity increased by 36.5, 5.5, and 11.0% for GPC0-S-25, GPCS-S-25, and GPCP-S-25, respectively, compared with GPC0-25, GPCS-25, and GPCP-25 specimens.

4. Conclusion

This research investigates the strengthening of FRGPC after high-temperature exposure using CFRP sheets, specifically GPC mixes based on MK and FA, utilizing two types of fibers (SF and PVA). The GPC cylinders underwent evaluation under ambient conditions and exposure to 500°C. The following conclusions were drawn:

1. The failure mode of heated specimens is similar to unheated specimens, with more fracture and crushing. Fiber incorporation improves GPC specimens' ductility. All the strengthened specimens failed due to the concrete crushing and the rupture of the CFRP wrap.
2. The slope of the stress–strain curve decreased as the temperature increased from 25 to 500°C. The strengthened

FRGPC specimens effectively enhanced the heated and unheated specimens' resistance and capacity for energy absorption by demonstrating increased confinement energy until they reached the CFRP rupture stresses. Ultimate strains at ultimate stress increased four times for strengthened specimens compared to unstrengthened specimens.

3. The incorporation of SF fiber (i.e., GPCS-25 specimens) slightly increased the strength by 2.5% compared to GPC0-25 specimens, while PVA fiber (i.e., GPCP-25 specimens) exhibited a decrease of 21.8%. In addition, the inclusion of SF fibers mitigated the decline in compressive strength after exposure to 500°C relative to GPC0-500 specimens.
4. The strength and ductility of all GPC mixes were substantially enhanced by the application of CFRP wraps. The compressive strength of unheated and heated strengthened specimens increased by up to 115.1 and 632.44%, respectively, compared with unstrengthened specimens at the same temperature degree.
5. The strengthening of heated specimens (i.e., those exposed to 500°C) by application of CFRP wrap increased the compressive strength up to 105.2% compared to unstrengthened specimens subjected to 25°C. Therefore, the original compressive strength was restored by strengthening heated GPC specimens using CFRP wraps.
6. The strengthening of FRGPC specimens with PVA fiber increased compressive strength by 9.2 and 10.8% when exposed to 25 and 500°C, respectively, compared to GPC specimens, despite a negative impact of PVA fiber on control GPC specimens.
7. The modulus of elasticity decreases as the temperature rises, regardless of fibers or CFRP wrap. At 500°C, the modulus of elasticity for the unstrengthened specimens was 7.4–10.3% of the value at 25°C, while it was 14.8–16.6% of the value at 25°C for the strengthened specimens.

The primary range of study is the use of a single high-temperature risk (500°C), which does not represent the full range of fire conditions. Future studies should detect a broader temperature spectrum and various fire periods. Additionally, the study was limited to cylindrical samples and a single fiber volume (1%), which needs to be examined in future studies. Moreover, microstructural analysis, such as using SEM or X-ray diffraction, needs to be examined in future studies.

FRGPC is an environmentally friendly option for traditional concrete, often made with industrial by-products such as FA or MK. Its improved mechanical properties, especially after fiber reinforcement, make it ideal for many applications, including: (i) fire-resistant structures:

a major application, as the GPC has better thermal stability than traditional concrete. It resists crushing and spalling at high temperatures, making it suitable for fireproof panels, tunnels, and structures where fire safety is a significant concern. (ii) post-fire recovery: the application of the CFRP sheet then restores or even enhances the mechanical properties of GPC, allowing the structure to be repaired and put back into service without the need for complete replacement. This combined technique is highly valuable for significant infrastructure where both fire resistance and rapid repairability are necessary.

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Author contributions

All authors contributed to the work equally.

Conflict of interest statement

Authors state no conflict of interest.

Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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