

Compressive behavior of metakaolin–fly-ash-based geopolymer fiber-reinforced concrete after exposure to elevated temperatures

Research Article

Yousef R. Alharbi, Aref A. Abadel*, Ali S. Alqarni, Abobaker S. Binyahya

Department of Civil Engineering, College of Engineering, King Saud University, Riyadh, 12372, Saudi Arabia

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Abstract: Portland cement production is responsible for 7% of the total carbon dioxide emissions around the world. Recently, there has been significant focus on developing environmentally sustainable construction products. Geopolymer concrete (GPC) is a sustainable material, and incorporating fibers can mitigate its brittleness while enhancing its overall performance, providing significant potential for various applications. Nonetheless, fire drastically reduces the structural strength and lifetime of reinforced concrete structures. To address this issue, this study investigates the compressive behavior of metakaolin–fly-ash-based geopolymer fiber-reinforced concrete after exposure to elevated temperatures. The GPC mixtures were made of steel fibers (SFs) and a combination of SF and polyvinyl alcohol (PVA) fibers, which were evaluated at exposure temperatures of 300 and 500°C. This investigation experimentally tests a total of 27 cylinders at 28 days, each with a diameter of 100 mm and a height of 200 mm. The results indicate that exposure of the GPC specimens to 300 and 500°C resulted in reductions of up to 24.2 and 45.2%, respectively. The inclusion of fibers had a slight effect on compressive strength, with the use of SF and hybrid fibers (SF + PVA) resulting in improvements of 8.1 and 7.5%, respectively. The addition of fibers significantly improved the post-peak response of both heated and unheated specimens, increasing the toughness index with ratios of up to 22.5 and 26.3% for the heated and unheated specimens, respectively.

Keywords: *Compression strength • Stress–strain curve • Elevated temperature • Fiber-reinforced concrete*

1. Introduction

There has been considerable interest in investigating geopolymer concrete (GPC) as a possible alternative to conventional cementitious binders. Geopolymers, also known as alkali-activated binders, are increasingly recognized as a sustainable alternative to ordinary Portland cement (OPC). They are produced by activating aluminosilicate materials in a very alkaline environment. Geopolymer manufacturing mostly uses materials containing both alumina and silica, including industrial byproducts like slag [1], fly ash (FA) [2], and red mud [3], as well as natural sources such as metakaolin (MK) [4]. Comprehensive studies have been conducted to evaluate the mechanical characteristics, chemical composition, microstructure, and high-temperature stability of geopolymer composites.

The compressive properties of MK–FA-based GPC at elevated temperatures represent a significant research focus, especially in light of the growing interest in sustainable construction materials. Geopolymers, derived from aluminosilicate minerals like FA and MK, demonstrate distinct thermal characteristics that affect their structural integrity at elevated temperatures. Studies demonstrate that the compressive strength of FA-based GPC often reduces when subjected to temperatures over 400°C, attributable to thermal inconsistency between the coarse particles and the geopolymer composite [5]. Nonetheless, at elevated temperatures of 600°C and higher, these materials may demonstrate enhanced compressive strength. This phenomenon is attributed to the densification of the microstructure and the emergence of supplementary amorphous phases, which augment the material's strength [6]. The addition of MK to FA-based geopolymers markedly enhances the compressive strength, especially at early

* E-mail: aabadel@ksu.edu.sa

ages, owing to heightened reactivity and the development of a denser microstructure [7].

Research indicates that MK-FA composites may maintain almost 50% of their compressive strength when subjected to temperatures above 700°C, highlighting their suitability for fire-resistant applications [8]. Furthermore, the spalling characteristics of these materials at increased temperatures have been examined, demonstrating that the combination of MK and FA can alleviate spalling, a common failure mode in concrete specimens exposed to high temperatures [9]. Fahim Huseien *et al.* [10] showed that geopolymers demonstrate superior mechanical and durability characteristics, such as minimal porosity, resistance to acids and sulfates, rapid early strength development, and high-temperature resilience. Temperature resistance significantly varies with mix design, affected by water content, precursor type, aggregate, and alkali levels. Fan *et al.* [11] studied the thermal characterization of FA-based geopolymer mortar subjected to 500 and 800°C, examining curing conditions, water-to-FA ratios, sealing levels, and cooling methods. No spalling was observed after exposure at both temperatures, irrespective of the cooling methods employed, whether natural or water-based. Junru *et al.* [12] evaluated FA-slag GPC matrix for residual tensile and compressive strength at 400–1,000°C. The compressive strength improved at 400°C, and geopolymer mixes outperformed OPC in residual strength. Zhang *et al.* [13] found that a 50% MK and 50% FA mix in GPC composites offers optimal strength at ambient and elevated temperatures up to 800°C, with strength degradation above 100°C. The MK-FA mix performed comparably to OPC under these conditions. Moradikhrou *et al.* [14] studied the effect of fibers on the axial strength of MK-based GPC at high temperatures (200–800°C). It was established that polypropylene, modified polypropylene, and polyolefin fibers exerted minor influence on the thermal resistance of the concrete. Tahwia *et al.* [15] investigated the compressive behavior of ultra-high-performance GPC with waste glass and ceramic after exposure to elevated temperatures. The experimental results indicated that the residual strength of specimens ranged from 98 to 97%, 59 to 63%, and 27 to 32% following exposure to temperatures of 300, 600, and 800°C, respectively.

Research indicates that the addition of fibers to concrete can enhance the compressive strength of GPC, although the results can vary significantly depending on the type and amount of fiber used. For instance, studies have shown that polyvinyl alcohol (PVA) fibers significantly enhance the compressive strength of geopolymer composites, with reported improvements as high as 40–70%, depending on the fiber content [16]. This enhancement is particularly beneficial at elevated temperatures, where the thermal stability

of PVA fibers contributes to maintaining the mechanical properties of the geopolymer matrix. Farhan *et al.* [17] found that the inclusion of 2% steel fibers (SFs) by volume significantly enhanced the compressive strength of alkali-activated concrete, indicating that SFs can substantially increase the load-carrying capacity and resistance to thermal cracking. Similarly, Wongruk *et al.* [18] reported that SF improved the overall mechanical properties of GPC, including compressive strength, particularly when subjected to elevated temperatures.

Research has demonstrated that increased temperature exposure affects the compressive strength of fiber-reinforced GPC. For example, whereas the compressive strength of GPC generally decreases at temperatures up to 400°C, some studies have reported that the strength can increase at temperatures around 800°C, particularly for fiber-reinforced samples [5]. This behavior is attributed to the thermal stability of the geopolymer matrix and the reinforcing fibers, which can enhance the overall performance of the concrete under fire conditions. Aygörmec *et al.* [19] studied the use of colemanite waste or silica fume as a substitute for MK in the polypropylene fiber-reinforced MK-geopolymer mortar that was subjected to temperatures as high as 900°C. Both compressive and flexural strength considerably decreased by exposure to high temperatures. Dhasindrakrishna *et al.* [20] observed that after being subjected to heat, the addition of PVA and carbon fibers, respectively, significantly enhanced the compressive strength of GPC. Nevertheless, a single type of fiber's ability to improve concrete is limited. Many researchers have turned their attention to the impact of hybrid fibers on GPC in order to better understand its overall performance.

However, to date, very few studies have investigated the combined effects of fibers on MK-FA-based GPC matrix. This article presents results on the compressive behavior of MK-FA-based GPC with hybrid fibers after exposure to temperature environments. Steel and PVA fibers were used in MK-FA-based GPC. In conclusion, the combined effects of the constituent ingredients of hybrid fibers affect the compressive behavior and thermal stability of MK-FA-based GPC at high temperatures.

2. Experimental program

2.1 Material properties

The primary component employed in this investigation was MK, which was obtained from kaolinitic soil samples collected from a deposit in the Riyadh region (Saudi Arabia) and then treated at 750°C for 3 h. The investigation

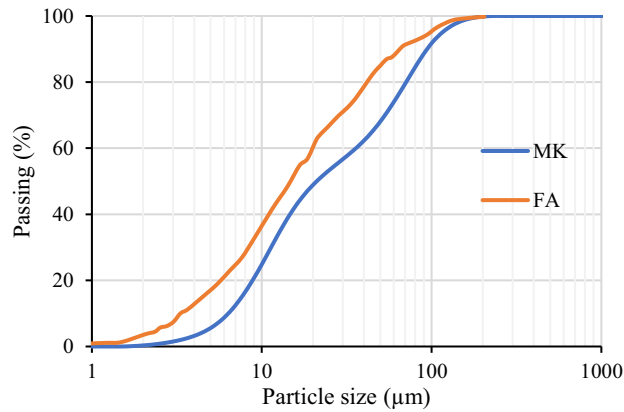


Figure 1. Particle size of MK and FA utilized in this investigation.

used a particle size analyzer machine to obtain the particle sizes of MK and FA, as illustrated in Figure 1. The MK's chemical composition is shown in Table 1. The GPC mix utilized fine and coarse aggregates, with crushed limestone (max size: 10 mm) as the coarse aggregate and a blend of crushed limestone (max size: 4.75 mm) and white sand (max size: 2 mm) as the fine aggregate. The GPC binding agent was activated using a sodium-based activator comprising sodium silicate (Na_2SiO_3) solution and sodium hydroxide (NaOH) solution. The NaOH solution with a concentration of 14 M was produced 1 day prior to preparing the specimen. The Na_2SiO_3 solution possessed a silica modulus of 3.3, representing the ratio of SiO_2 to Na_2O . The mix used for the production of fiber-reinforced concrete incorporated two varieties of fibers: (i) PVA fibers (PVA with a chemical formula $(\text{C}_2\text{H}_4\text{O})_n$) and (ii) hooked-end SFs, sourced from KURARAY Co., Ltd, Japan, and Ganzhou Daye Metallic Fibres Co., Ltd, China, respectively. Figure 2 and Table 2 depict the characteristics of the two fiber types (i.e., PVA and SF) employed in the investigation. The FA utilized in this experimental work was classified as Class F according to ASTM C618 [21].

2.2 Mixture proportions

Table 3 illustrates the proportions of the ingredients employed in formulating GPC mixtures. Table 4 presents

the quantities of SF, PVA, or combination (i.e., SF + PVA) fibers in the GPC mixtures. This study entailed the formulation of two composites of fiber-reinforced concrete. The control mixture (M0) was prepared without fibers, the second mixture (MS) was incorporated with SF, and the third mixture (MSP) included both steel and PVA fibers. Additionally, Table 4 presents the test matrix employed in the experimental scheme of this study. Each test cylindrical specimen underwent three replicates to ensure data consistency and enhance confidence in the

Properties	Fiber	
	SF	PVA
Shape	Hooked ends (circular cross section)	Straight (circular cross section)
Diameter (mm)	0.75	0.06
Length (mm)	60	12
Aspect ratio	80	200
Tensile strength (MPa)	1,225	1,600
Young's modulus (MPa)	200,000	35,000
Density (kg/m^3)	7,850	1,300

Table 2. Fiber characteristics.

Composition	SiO_2	CaO	Fe_2O_3	Na_2O	Al_2O_3	TiO_2	SO_3	K_2O	P_2O_5	MgO	Others
Value (%)	50.995	1.287	2.114	0.284	42.631	1.713	0.439	0.337	0.051	0.127	0.022
	61.30	0.28	4.39	0.12	24.80	0.80	0.39	1.49	0.45	0.74	5.26

Table 1. MK's chemical analysis (% weight).

Material	Weight
MK	277.2
FA	118.8
NaOH solution	92
Na ₂ SiO ₃ solution	291.3
Fine aggregate Crushed limestone (max size: 4.75 mm)	449.8
White sand (max size: 2 mm)	148.4
Coarse aggregate Crushed limestone, max size: 10 mm)	1365.8

Table 3. GPC mixture proportions in kg/m³.

findings of the investigation. This investigation used a total of 27 cylinders, each with a diameter of 100 mm and a height of 200 mm. The testing program considered the following primary variables: (i) the performance of various fiber types (SF, PVA, and both SF and PVA fibers) and (ii) evaluated temperature damage (exposed to temperatures of 25, 300, and 500°C).



(a)



(b)

Figure 2. Fiber types: (a) SF and (b) PVA.

2.3 Specimen preparation

The aggregates of all mixtures were used in the saturated surface dry phase and then subjected to a dry mixing process with MK for a duration of 2 min. The mixed alkaline solutions (NaOH and Na₂SiO₃) were added into the dry concrete constituents. The mixing process continued for several minutes until the mixture reached a homogeneous state. In the preparation of MS and MSP mixtures, fibers were incorporated into the mixture, and the mixing process was maintained for a minimum duration of 4 min. GPC was gradually poured into the molds to minimize separation and prevent void formation, utilizing a vibrating table for this purpose. Figure 3 illustrates the process of GPC vibration during casting in molds. The uppermost layer was carefully leveled with a steel trowel to ensure a uniform surface. The specimens were cured for a duration of 28 days under laboratory conditions, within an ambient temperature of $24 \pm 2^\circ\text{C}$ and a relative humidity of $20 \pm 2\%$. Table 4 presents the test specimen matrix utilized in this study. Moreover, Table 4

Mixture ID	Specimens ID	Temperatures (°C)	Fiber volume			No. of specimens
			SF	PVA	Total	
M0	M-25	25	—	—	—	3
	M-300	300	—	—	—	3
	M-500	500	—	—	—	3
MS	MS-25	25	1%	—	1%	3
	MS-300	300	1%	—	1%	3
	MS-500	500	1%	—	1%	3
MSP	MSP-25	25	0.7%	0.3%	1%	3
	MSP-300	300	0.7%	0.3%	1%	3
	MSP-500	500	0.7%	0.3%	1%	3
Total no. of specimens						27

Table 4. Test matrix utilized in the experimental scheme of the current study.



Figure 3. GPC cylindrical specimens during casting.

employs the abbreviations “M0,” “MS,” and “MSP” to denote different types of GPC mixtures: M0 represents control GPC mixtures without fibers, MS GPC mixtures with SFs, and MSP GPC mixtures with hybrid fibers (i.e., SF + PVA). The specimen identifiers comprised alphanumeric characters. The initial string refers to the specific GPC mixtures used. The designations “25,” “300,” and “500” indicate the specimens subjected to temperatures of 25, 300, and 500°C, respectively.

2.4 Heating of concrete samples

The GPC specimens were subjected to heating in an electrically powered oven until they attained the required temperatures of 300 and 500°C. The specimens were relocated from the laboratory to the oven 1 day prior to the testing. The oven heated the GPC specimens at an elevated average rate of 8 °C/min until they reached temperatures of 300 and 500°C. The heating process continued for 3 h before it

ended. Thereafter, the GPC specimens were allowed to cool down to room temperature. The time–temperature curves of GPC specimens used in this study upon exposure to 300 and 500°C are shown in Figure 4. These curves are compared to the standard curve in ISO 834 [22]. The GPC specimens were subsequently allowed to cool at room temperature for a duration of 24 h before undergoing testing.

2.5 Testing protocol

In this research, uniaxial compression was applied to the GPC specimens. The upper surface of the specimen was coated with sulfur to ensure complete leveling during the testing process. Each GPC specimen was included in a compressometer to measure the axial strain over the test, as illustrated in Figure 5. Two linear variable differential transducers (LVDTs) were included on two circular sleeves that surrounded the GPC specimen within the compressometer. The sleeves were firmly affixed to the GPC specimen with pin-type support to ensure they did not affect the dilation of the specimen. Uniaxial compression was imposed on the GPC specimens until failure occurred. The compressive strength of the specimens was evaluated according to the method outlined in ASTM C39 [23].

3. Results and discussion

3.1 Failure modes

Figure 6 illustrates the prevalent failure patterns observed in all GPC specimens following compression testing and exposure to temperatures of 25, 300, and 500°C.

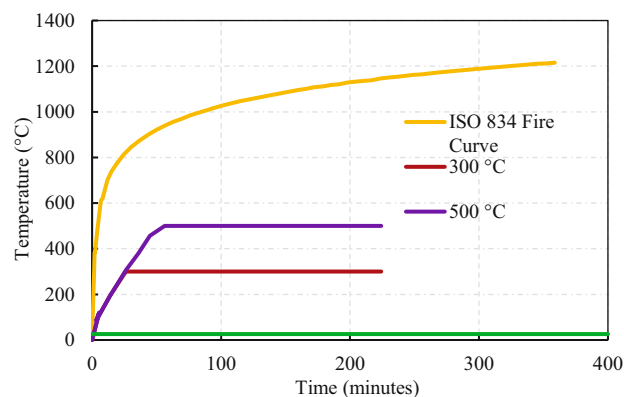


Figure 4. Time–temperature curves of GPC cylinders used in the current study.



Figure 5. Test setup used in the current study.

Significantly, none of the examined GPC specimens subjected to varying degrees of heat temperatures (300 and 500°C) exhibited obvious corner fracture or spalling. Furthermore, no significant cracks were observable even after exposure to higher temperatures reaching 500°C. The control specimens (i.e., those without fibers) underwent brittle failure due to concrete crushing, as shown in Figure 6. Upon exposure to elevated temperatures, the heated control specimens (i.e., those without fibers) exhibited a diminished propensity for brittle failure. The concrete cover exhibited initial indications of spalling. Consequently, a failure occurred when the axial load began to decrease, in contrast to specimens of the same type that were exposed to a temperature of 25°C. When exposed to temperatures of 300 and 500°C, surface cracking due to heating was visible on the GPC specimens without fibers. GPC specimens without fibers exhibited significant cracking with the increase of temperature, characterized by noticeable fragmented fissures that did not detach completely. The matrix structure of heated specimens without fibers became brittle, exhibiting numerous cracks and a larger peeling area compared to those with fibers. Generally, the failure pattern observed in the heated specimens closely matches with that of the unheated specimens. Compared to the unheated specimens, the heated specimens showed more fracture and crashing. This can clarify why the compressive strength of heated specimens did not exceed that of specimens at ambient temperature. GPC specimens exhibited higher rates of cracks and fractures when exposed to a temperature of 500°C compared

to those exposed to 300°C, as illustrated in Figure 6. The exposure to temperatures of 300 and 500°C led to the occurrence of thermal cracking on the specimens' surfaces. Generally, the failure sound was lower for the heated specimens, whereas the unheated specimens made a loud sound, like a small explosion, when they failed. As a result, there was no abrupt failure, unlike specimens of the identical type subjected to ambient temperature. Furthermore, Albidah *et al.* [24] found no large cracks even when exposed to elevated temperatures of up to 600°C, which is consistent with previous research findings. The M-25 specimen exhibited significant cracks and crushing, first observed at the load application area and later progressing toward the specimen's midpoint. The MS-25 and MSP-25 cylinders showed different patterns. Surface thermal cracks were still present, but the fibers in the mixtures significantly decreased their occurrence. The specimens incorporating SF (i.e., MS-25) demonstrated reduced crack widths relative to that of the M-25 specimen, as depicted in Figure 6. Substantial parts of concrete remained detached but had not yet fallen, showing that the fibers served a protective function against cracking following elevated temperatures. Elsanadedy *et al.* [25] reported that adding SF and hybrid fibers (SF + PVA) to the GPC mixture facilitated the bridging of cracks. These outcomes agree with the findings of the current study. At high temperatures, the GPC specimens containing fibers showed significant peeling on their middle surfaces, indicating a diminished bonding strength between the GPC matrix and SFs. However, the inclusion of fibers modified the failure mode of GPC specimens, changing it from a brittle to a ductile state by enhancing the mixture's toughness, aligning with previous research findings in cement concrete and GPC [26]. GPC specimens without fibers often fail in a way that is either brittle or explosive. Specimens with fibers, on the other hand, were less brittle and explosive due to the arbitrary distribution of fibers inside the GPC matrix. The failure behavior of specimens exposed to heat that contained SFs exhibited increased ductility. The enhanced ductility may be attributed to the bonding influence between the concrete matrix and SF, which reduced the crack propagation and formation while maintaining load resistance at the cracks. The presence of fibers mitigated the negative effects of increased porosity following evaluated temperatures, reduced the crack size, and enhanced the strength. The failure mechanism of heated GPC specimens with hybrid fibers (SF + PVA) exhibited features similar to those of cylinders containing SFs.

3.2 Compressive strength

Figure 7 displays the average values of compressive strengths of the three specimens for each mixture. The unheated GPC

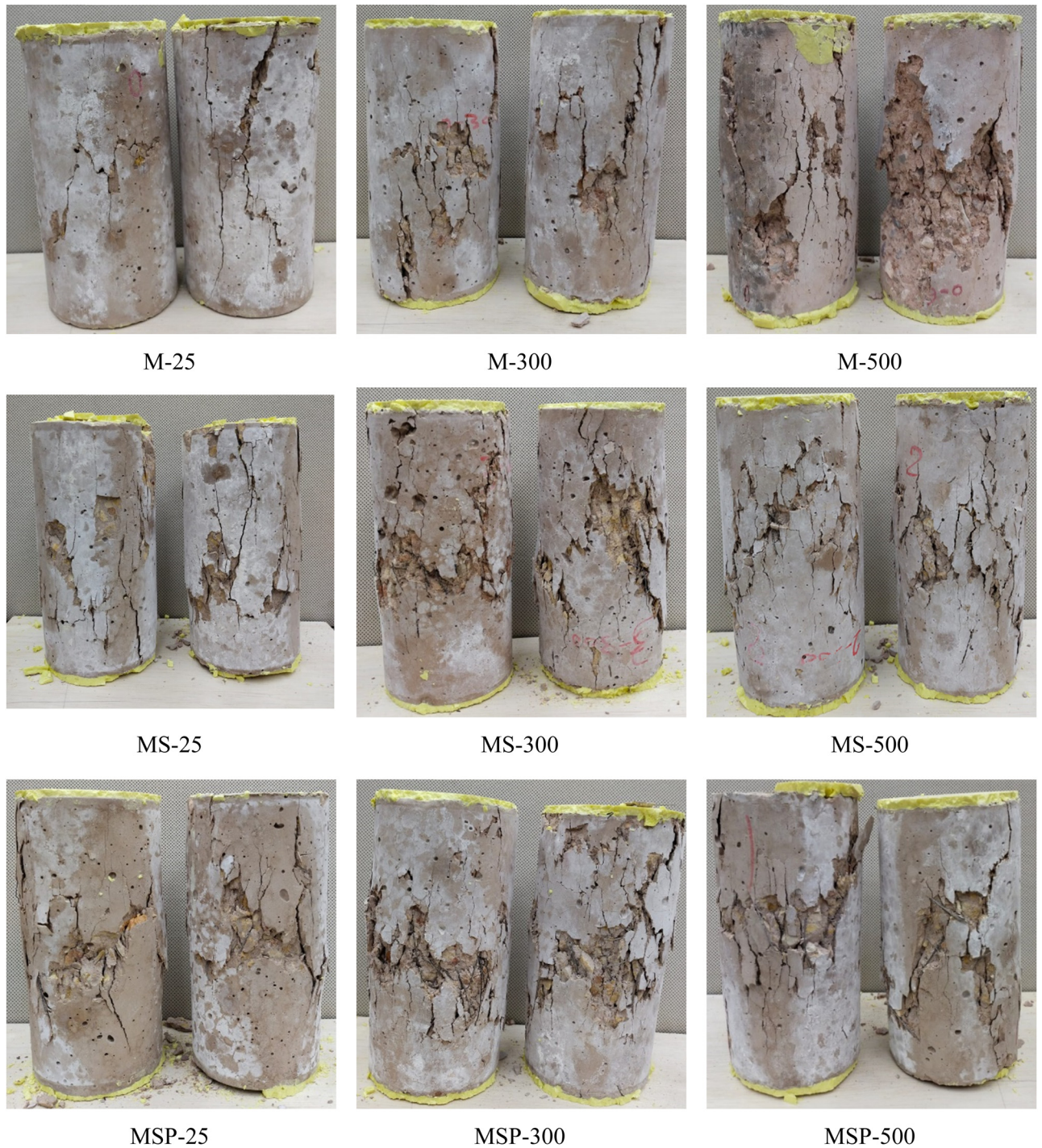


Figure 6. Failure modes of representative specimens.

specimens exposed to an ambient temperature of 25°C yielded a compressive strength of 41.94 MPa for the M-25 mixture after a curing period of 28 days. The addition of SF (i.e., the MS-25 mixture) resulted in a compressive strength

of 45.32 MPa, indicating a slight increase of 8.1% in comparison to the M-25 mixture. The same trend was noticed with the hybrid fibers; the MSP-25 mixture demonstrated a compressive strength of 45.10 MPa, indicating an increase of

7.5% compared to the M-25 mixture. The previous research indicated that the incorporation of SFs in concrete mixtures can slightly enhance the compressive strength while significantly improving the ductility [27]. Thomas and Ramaswamy [28] performed an experimental investigation to examine the influence of hooked-end SFs on the mechanical characteristics of various concrete grades with compressive strengths of 35–85 MPa. They added the SF in three volume fractions (0.5, 1.0, and 1.5%). Their findings revealed a relatively minor enhancement in compressive strength, less than 10%, across various classes of concrete. These outcomes agree with the findings of the current study. The enhanced compressive strength of the GPC mixture with fibers may be attributed to the bonding influence between the concrete matrix and SFs, which reduces crack propagation and formation while maintaining load resistance at the cracks [29]. The same trend was observed for the hybrid fiber mixture (i.e., MSP-25). Other research has also concluded that PVA fibers have a negligible effect on the compressive strength of GPC mixtures [30,31], and in some cases a negative influence has been observed [32,33]. Therefore, it can be inferred that only a small amount of PVA fibers may substantially boost the compressive strength of the GPC mixture. It appears to be established that PVA fibers do not influence the compressive strength of the GPC mixture, as previously concluded. The PVA fibers are challenging to disperse, often resulting in voids and defects within the matrix. Increasing the air content in the mixture subsequently reduces the density of concrete specimens [34].

Figure 7 demonstrates the difference in compressive strength at ambient temperature and 300°C. The compressive

strength of heated specimens decreased by 24.2, 27.5, and 23.6% for M-300, MS-300, and MSP-300, respectively, in comparison to the unheated specimens M-25, MS-25, and MSP-25. The deterioration rate of the compressive strength diminished with the addition of fibers (i.e., SF or SF + PVA). The decrease in compressive strength of GPC exposed to elevated temperatures is attributable to the disparity in expansion during heating between the GPC matrix and aggregate, causing cracks and degradation of the bond at the aggregate–paste interface, as highlighted by Kong and Sanjayan [35]. Furthermore, when exposed to 300°C, water present within the GPC matrix migrates to the external surface of heated specimens and subsequently evaporates. This procedure predominantly transpires within the temperature range of 100–300°C, and beyond that point water evaporation decreases, and the reduction rate of strength deterioration decreases with higher temperatures [13]. Moreover, this procedure leads to the degradation of the internal microstructure and a reduction in compressive strength [13]. As reported by Albidah *et al.* [26], the SEM examination indicated that the micrographs obtained after heating at 400°C exhibited an approximate porosity and a sponge-like structure in the GPC mixtures, which contributed to the reduction in strength. Following the exposure of GPC specimens to a higher temperature of 500°C, a similar trend was observed in the specimens heated to 300°C. The compressive strength of heated specimens decreased by 45.2, 45.3, and 40.7% for M-500, MS-500, and MSP-500, respectively, in comparison to the unheated specimens M-25, MS-25, and MSP-25. The results of this study confirm the viability of MK–FA-based GPC as a substitute for the traditional

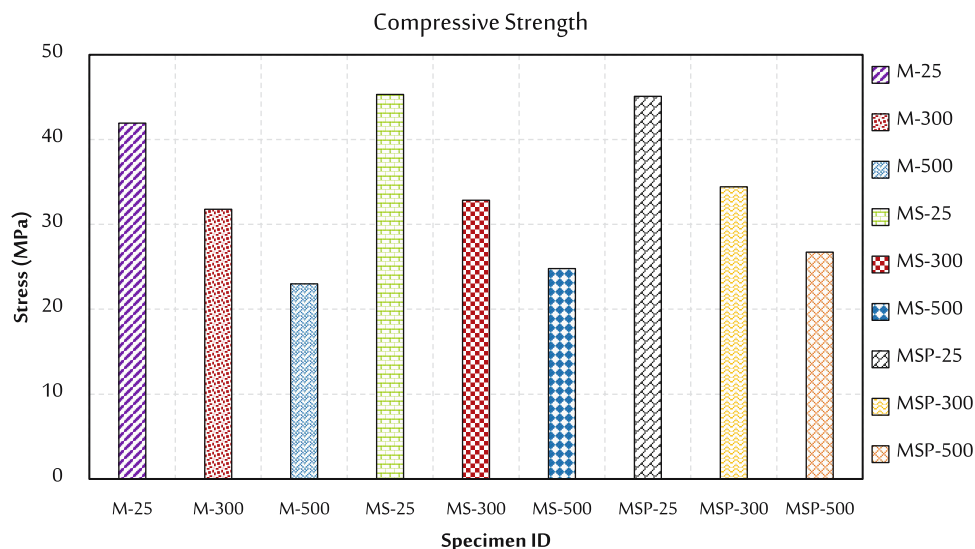


Figure 7. Compressive strength of all specimens.

Portland cement-based concrete. Research demonstrates the feasibility of achieving compressive strengths that are comparable to or slightly exceeding the values of conventional concrete.

Figure 8 illustrates the fluctuation of concrete's relative compressive strength in relation to temperature for the current study results (M0, MS, and MSP curves) compared to previous studies [36,37]. The same trends were noticed in the strength loss for the normal strength concrete specimens (Figure 8a). However, the GPC specimens exhibit superior resilience to fragmentation in comparison to normal-strength concrete specimens. A slight superiority was noticed for the GPC specimens compared to high-strength concrete specimens (Figure 8b). The variations in material composition due to regional availability, historical curing temperatures, curing cycles, concrete age, and the utilization of diverse furnace types complicate the provision of a generalized interpretation.

3.3 Stress–strain curves

The stress–strain curves of concrete are an important consideration in evaluating the overall performance of concrete mixtures subjected to high temperatures (300 and 500°C). Figure 9 presents the stress–strain curves for all specimens. By dividing the compressive load by the specimen's cross-sectional area, the stress was determined. The vertical displacement (as measured by the LVDTs) was divided by the LVDT gauge's length to determine the strains. The unheated specimens displayed a uniform linear increase of stresses in the initial loading steps. The elastic modulus diminishes with an increase in temperature from 25 to 500°C, as demonstrated by the stress–strain curves. The strains were rather minimal during the elastic phase, as illustrated in Figure 9b. Figure 9c illustrates a similar tendency, with the heated specimens at 300°C exhibiting greater strains than the unheated

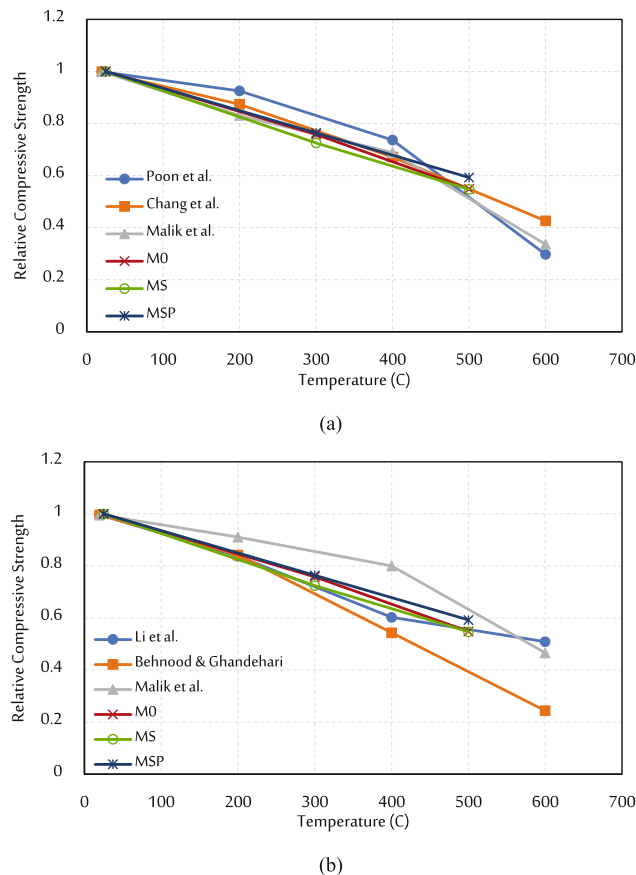


Figure 8. Relative compressive strength: (a) normal strength concrete [36,38,39] and (b) high strength concrete [36,37,40].

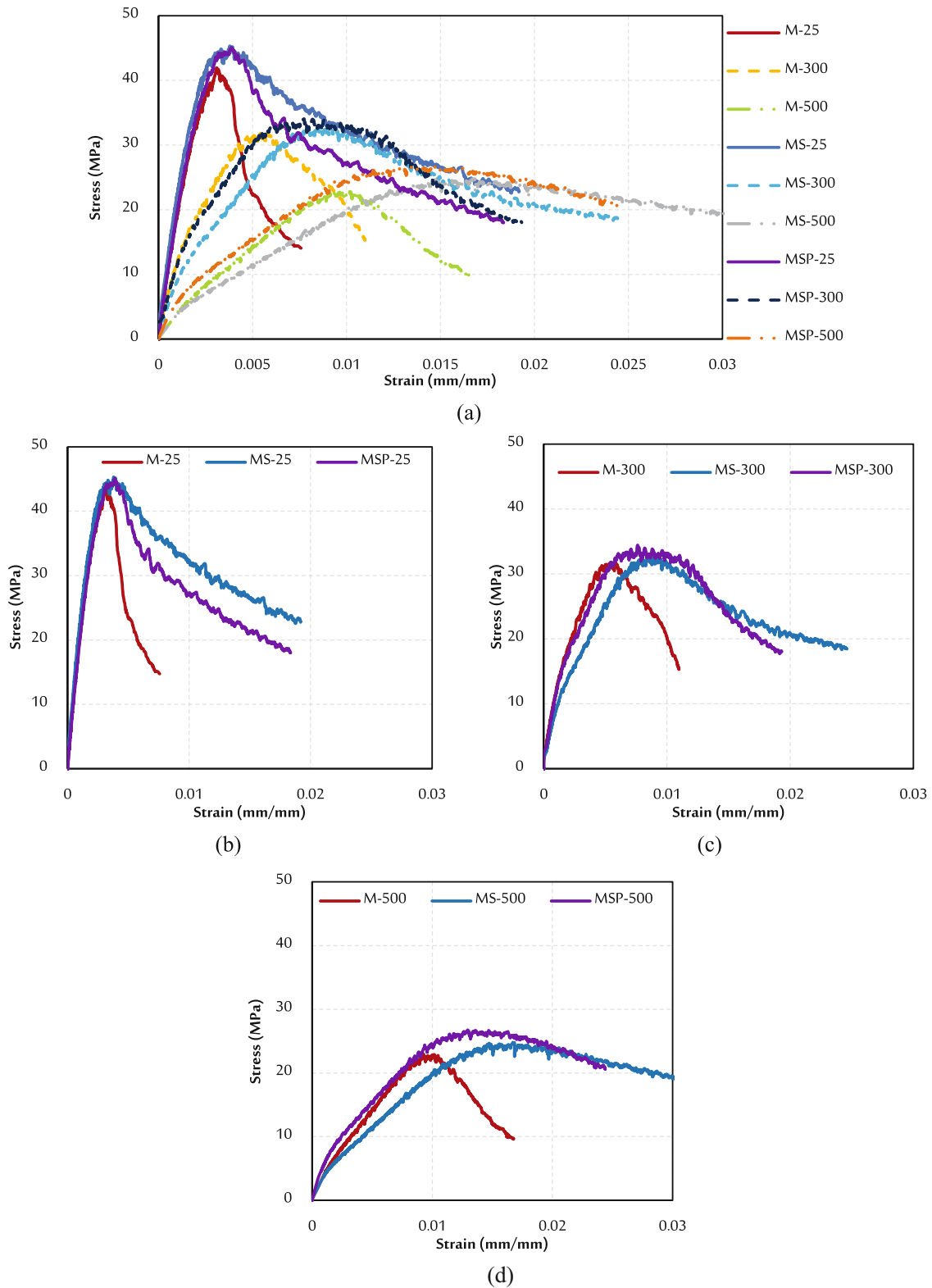


Figure 9. Stress–strain curves: (a) all specimens, (b) specimens at 25°C, (c) specimens at 300°C, and (d) specimens at 500°C.

specimens. The heated specimens at 500°C show a significant drop in stress and higher strains during the elastic phase compared to all other specimens (Figure 9d). With the increase of load, the stress progressively approached the maximum values. Increasing the temperature from ambient to 500°C resulted in an increase in the strain at peak stress. The strain at peak stress for GPC specimens evaluated at ambient temperature ranged from 0.0031 to 0.0039. The range was significantly higher, varying from 0.0057 to 0.0094 and 0.0103 to 0.0168 for specimens subjected to 300 and 500°C, respectively. The curves began to exhibit nonlinear behavior as the stress neared the maximum values, beyond which the slope of the curve decreased and nearly all strain measurements exceeded the yield strain values. Before failure, GPC specimens exhibit a notable reduction in stress. Generally, the stress–strain curves for the GPC mixtures with fibers are uniform for the beginning slope of the curve, peak stress, and associated strain. The GPC specimens with fibers (SF or hybrid fibers) demonstrated a gradual reduction in the stress–strain curve. The fibers' ability to crack bridging resulted in enhanced ductility after reaching the ultimate stress, as demonstrated in Figure 9. While the heated GPC specimens demonstrated a decrease in ultimate stress, the curves did not demonstrate a sudden drop. Mixtures containing fibers showed increased rigidity. The increase in stiffness with fibers was analogous to 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. The curves indicate that both GPC mixtures, with and without fibers, experience a more considerable reduction in initial stiffness when subjected to a temperature of 300 and 500°C, as illustrated in Figure 9c and d. Subjecting to a temperature of 300–500°C results in a decrease in stress due to the reduction of moisture content and the degradation of cement paste

hydration. Further research [41] has similarly confirmed that the strength of fiber-reinforced concrete mixtures significantly diminishes when subjected to temperatures beyond 600°C. The pure PVA undergoes degradation in two distinct phases, occurring within temperature ranges of 300–450°C and 450–550°C, respectively [24,42]. While degradation may have commenced at 400°C, it is not quite complete. Consequently, the cooling of the residue following the melting of fibers facilitates the binding of aggregate particles. The inclusion of SF in the hybrid combination enhanced the deficiencies of the PVA fibers. This may have contributed to the function of fibers at elevated temperatures by preventing cracking and exhibiting a superior response when used with SF as a hybrid compared with SF alone. Figure 9a and Table 5 show that the MS-25 specimens have the highest peak stresses for all the specimens. Moreover, the MSP-25 showed comparable peak stresses, with a slight reduction (0.5%) compared with MS-25 specimens. This means that the fibers (SF and SF + PVA) effectively increased the GPC specimens' resistance to heating. Even when exposed to temperatures of 300 and 500°C, the influence of fibers significantly outperformed the control mixture in the analysis of the post-peak response of the curves, as demonstrated in Figure 9. Furthermore, the GPC specimens with fibers exhibited an enhanced capacity for absorbing energy (quantified by the area under the curve), in contrast to the GPC specimens without fibers. A comparable finding was noted in prior research [43].

3.4 Effectiveness of fiber type variations

The compressive strength of heated and unheated GPC specimens is shown in Table 5. A comparison was made to evaluate the contribution of fibers to compressive strength following exposure to high temperatures (300

Specimens	Compressive strength (MPa)	Relative difference (%) ^a	Initial stiffness (N/mm)	Relative difference (%) ^a	Toughness index (%)	Relative difference (%) ^a
M-25	41.94	—	19,853.3	—	2.38	—
M-300	31.79	24.2	11,560.0	41.8	1.77	25.3
M-500	23.00	45.2	31,88.9	83.9	1.38	41.9
MS-25	45.32	—	23,696.7	—	2.91	—
MS-300	32.85	27.5	7,300.0	69.2	2.25	22.8
MS-500	24.80	45.3	2,387.5	89.9	1.87	35.7
MSP-25	45.10	—	19,933.7	—	3.07	—
MSP-300	34.44	23.6	10,933.3	45.2	2.19	28.5
MSP-500	26.73	40.7	4,096.6	79.4	1.78	41.9

^aThe control sample in each GPC mixture is used as a reference sample.

Table 5. Summary of test results.

and 500°C). This details the strength retained by concrete after being subjected to elevated temperatures in comparison with its strength at 25°C (ambient temperature). The findings revealed that the addition of fibers has a considerable effect on compressive strength, independent of the fiber type employed. The incorporation of fibers effectively minimized the reduction in compressive strength observed after exposure to high temperatures (300 and 500°C) when compared to GPC mixtures lacking fibers. The reduction in the compressive strength of heated specimens containing fibers exposed to 300°C is less compared to that of the control GPC specimen. MS-300 and MSP-300 demonstrated ratios of 21.7 and 17.9%, respectively, while M-300 had a reduction ratio that reached 24.2% when compared to the M-25 specimen. The compressive strength of heated specimens for M-300, MS-300, and MSP-300 was, respectively, 24.2, 27.5, and 23.6% lower than that of their unheated specimens, M-25, MS-25, and MSP-25. The specimens exposed to 500°C demonstrated the same tendency. The compressive strength of heated specimens for M-500, MS-500, and MSP-500 was, respectively, 45.2, 45.3, and 40.7% lower than that of their unheated specimens, which were M-25, MS-25, and MSP-25. The increase in temperature from 300 to 500°C resulted in a significant deterioration of pressure resistance. Specifically, the decrease at 300°C reached 27.5%, whereas the decrease at 500°C reached 45.3% when compared to their unheated specimens. Table 5 indicates that the MS-25 specimens exhibit the highest peak stresses among all the specimens analyzed. Furthermore, MSP-25 exhibited similar peak stresses, demonstrating a minor decrease of 0.5% in comparison to the MS-25 specimens. The fibers (SF and SF + PVA) significantly enhanced the GPC specimens' resistance to heating. Despite the exposure to temperatures of 300 and 500°C, the

impact of fibers clearly exceeded that of the control mixture in the examination of the post-peak response of the curves, as illustrated in Figure 9. Furthermore, SFs can withstand high temperatures. The function of crack bridging reduces the propagation and formation of fractures, allowing the concrete specimens to consistently endure axial stresses, even in the existence of cracks [44–46]. Although PVA fibers are shorter and have a lower Young's modulus compared to SFs, they are capable of bridging microcracks, as demonstrated in previous work (e.g., the study of Zhang et al. [47]).

3.5 Impact of fiber on the initial stiffness

The stiffness of the reinforced concrete components significantly influences the load distribution in reinforced concrete constructions. Therefore, the fibers employed to strengthen heated specimens must restore both their compressive strength and stiffness. Assessing the initial stiffness of GPC mixtures is essential for understanding the impact of high temperatures on the elasticity of GPC mixtures. The initial stiffness was calculated as the stress-to-strain ratio measured at 40% of the ultimate stress. The GPC specimens showed no cracks at this stress stage. Table 5 displays the initial stiffness values. The initial stiffness of the heated GPC specimens exhibited a significant reduction, as illustrated in Table 5 and Figure 10. Exposure to high temperatures (300 and 500°C) resulted in a significant decrease in initial stiffness, even in the presence of fibers. When compared to the unheated concrete cylinders, the heated GPC cylinders showed a reduction in initial stiffness of up to 45.2 and 84.2% at 300 and 500°C, respectively. The heated specimens M-300 and M-500 showed a

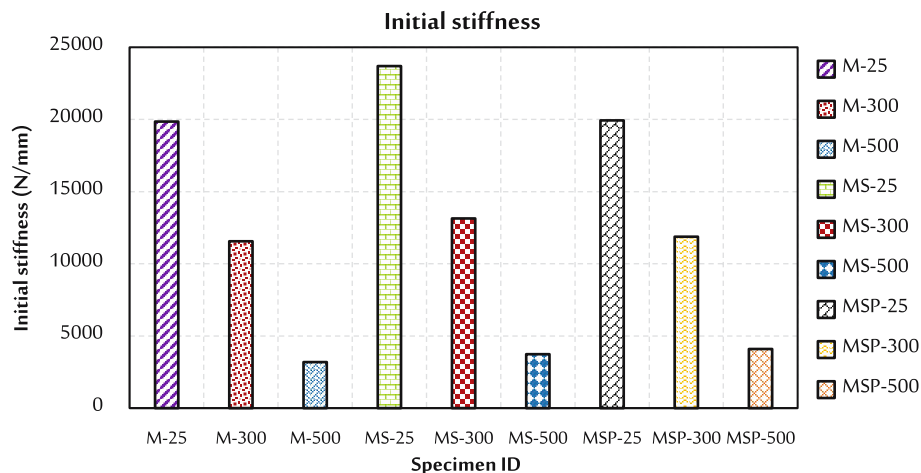


Figure 10. Initial stiffness of all specimens.

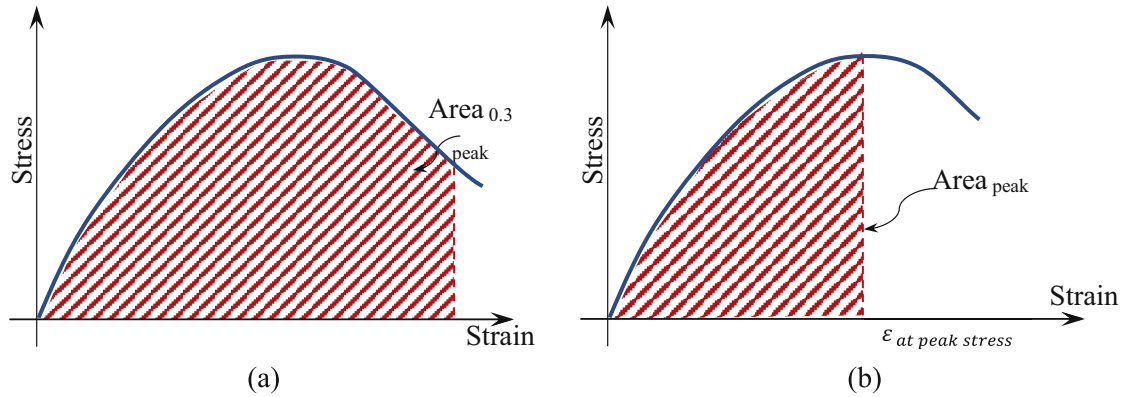


Figure 11. Initial stiffness of all specimens: (a) the area under the curve until 0.3 peak stress (in the decreased portion) and (b) the area under the curve until peak stress.

reduction in initial stiffness of 41.8 and 83.9%, respectively, when compared to the unheated specimen M-25. Additionally, a similar trend was observed when SF and hybrid fibers were used. The reduction ratios for MS-300, MSP-300, MS-500, and MSP-500 specimens were 44.5, 45.2, 84.2, and 79.4%, respectively, in comparison to the unheated specimen of each mixture. The heated specimens with fibers exhibited an enhancement of initial stiffness relative to the heated specimens without fibers. The initial stiffness for MS-300, MSP-300, MS-500, and MSP-500 specimens showed increases of 12.0, 2.7, 14.7, and 22.2%, respectively, in comparison to the heated specimen without fibers (i.e., M-300 and M-500). The reduction in the initial stiffness can be due to the development of microcracks

caused by elevated temperatures and consequently evaporated water, leading to pore structure creation in the heated specimens. Consequently, when specimens undergo axial compression, heated specimens are anticipated to demonstrate a greater extent of lateral expansion than their unheated specimen counterparts [48].

3.6 Toughness index

The toughness index of GPC specimens subjected to compression tests after being exposed to high temperatures was determined according to the approach developed by Zheng et al. [49]. According to this approach, the toughness

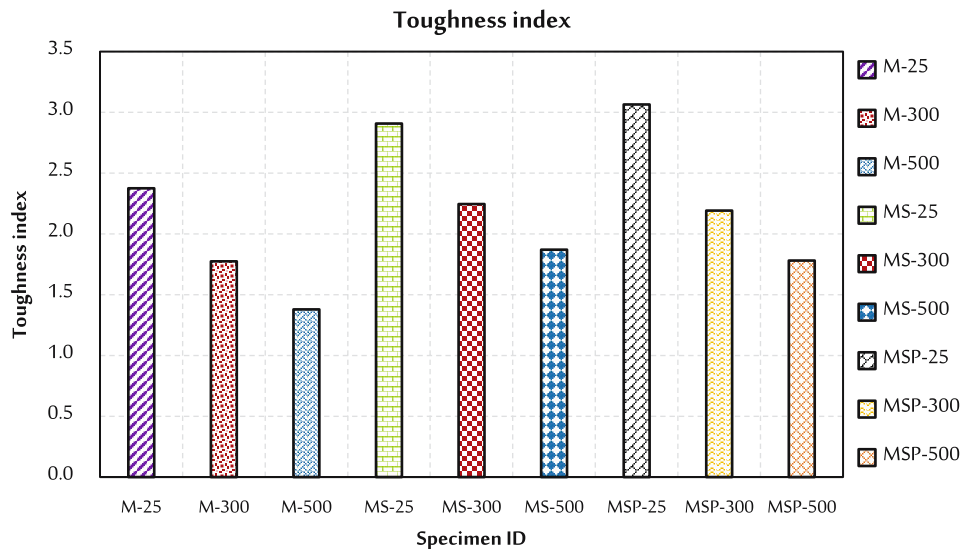


Figure 12. Toughness index of all specimens.

index is the area under the stress–strain curve after peak stress (which decreases up to 30%) divided by the area up to the peak stress, as illustrated in Figure 11. Table 5 shows the toughness indices of all specimens.

$$\text{Toughness index} = \frac{\text{Area}_{0.3 \text{ peak}}}{\text{Area}_{\text{peak}}} \quad (1)$$

Table 5 and Figure 12 present the toughness index of all mixtures. The results demonstrated that the inclusion of fibers led to improved toughness in GPC mixtures relative to the control mixture (i.e., without fibers). The toughness index increased from 2.38 for the control mixture (M-25) to 2.91 and 3.07 in the MS-25 and MSP-25 specimens, respectively, at ambient temperatures. The investigation finds that incorporating fibers into GPC mixtures improves the post-peak response by making the degradation of compressive strength after reaching the peak more gradually. In contrast, the GPC mixtures without fibers show a sudden drop in stress. It is evident that when the temperature increases, the toughness index decreases. The increase in temperature (from 25 to 500°C) degrades structural characteristics. Furthermore, elevated temperatures weaken the bond between the GPC matrix and fibers, thereby reducing the effectiveness of toughness. When compared to M-25, MS-25, and MSP-25 (i.e., unheated specimens), the toughness index of M-300, MS-300, and MSP-300 (i.e., heated specimens) decreased by 25.3, 22.8, and 28.5%, respectively. A similar pattern was noted when the GPC specimens were subjected to temperatures of 500°C. When compared to M-25, MS-25, and MSP-25 specimens, the toughness index of M-500, MS-500, and MSP-500 specimens decreased by 41.9, 35.7, and 41.9%, respectively. The toughness index of M0 mixtures diminishes more than that of MS and MSP (i.e., with fibers) mixtures after exposure to high temperatures. Fiber mixtures' bonding capability and structure mitigate the negative impact of elevated temperatures. The toughness index of fiber mixtures consistently remains higher than that of M0 mixtures at the same high temperature. Figure 12 and Table 5 illustrate that the MSP-25 specimens have the highest toughness index. Moreover, MS-25 showed a comparable toughness index, with a slight reduction (5.1%) compared with those of MSP-25 specimens. This means that the fiber (SF and SF + PVA) effectively increased the toughness of GPC specimens. Even when exposed to temperatures of 300 and 500°C, the influence of fibers significantly outperformed the control mixture in the analysis of the post-peak response of the curves, as demonstrated in Figures 9 and 12. Although PVA fibers may melt at high temperatures, the residual melted fibers, combined with SF, have improved the toughness index.

4. Conclusions

This study examines the compressive behavior of heated-damaged MK–FA-based geopolymer fiber-reinforced concrete using two fiber types (SF and PVA). Furthermore, the GPC cylinders were evaluated under room conditions and exposed to 300 and 500°C. The following conclusions were derived:

1. The exposure to high temperatures led to a decrease in the compressive strength of GPC specimens. Exposure of the specimens to 300 and 500°C resulted in a reduction of up to 24.2 and 45.2%, respectively.
2. The inclusion of fibers had a slight effect on compressive strength, with the use of SF and hybrid fibers (SF + PVA) resulting in improvement of 8.1 and 7.5%, respectively.
3. The heated GPC specimens exhibited significant crushing and cracks compared to unheated GPC specimens. The incorporation of fibers led to a reduction in thermal cracking and transformed the failure mode to ductile.
4. The presence of fibers mitigates the adverse effects of exposure to 300 and 500°C, causing the initial stiffness of specimens to increase by up to 12.0 and 22.2%, respectively.
5. The addition of fibers significantly improved the post-peak response of both heated and unheated specimens, increasing the toughness index with ratios of up to 22.5 and 26.3% for the heated and unheated specimens, respectively.
6. The use of SF (MS-25 specimens) exhibited the highest peak stresses, whereas the hybrid fibers showed the highest toughness index of all the specimens. Although PVA fibers may melt at high temperatures, the residual melted fibers, combined with SF, have improved the toughness index.

The authors recommend investigating the long-term durability of fiber-reinforced GPC following exposure to elevated temperatures to enhance the understanding of its performance compared to conventional concrete.

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Author contributions

Yousef R. Alharbi: formal analysis, investigation, data curation, fund acquisition, writing – original draft, and writing –

review and editing. Aref A. Abadel: conceptualization, methodology, formal analysis, investigation, data curation, visualization, fund acquisition, project administration, writing – original draft, and writing – review and editing. Ali Alqarni: visualization, investigation, and writing – review and editing. Abobaker Salem: visualization, project administration, and editing of the manuscript.

Conflict of interest statement

There is no conflict of interest to declare.

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