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Enhancing Fire Resistance of Geopolymer Concrete Through Steel Fiber Reinforcement: Microstructure and Mechanical Behavior at Elevated Temperatures

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Abstract. This paper investigates the thermo-mechanical performance of steel fiber reinforced GPC using a combination of fly ash (FA), ground granulated blast furnace slag (GGBS), and ordinary Portland cement (OPC) in binder. The geopolymer matrix was activated with a binary solution containing sodium silicate–sodium hydroxide and the alkaline activator–to–binder by mass for 0.40, with hook-end steel fibers added at volume contents of 0%, 0.5%, 0.75%, and 1.0%. In addition, its mechanical properties such as compressive, split tensile and flexural strengths were tested at room temperature before and after exposure to high temperatures of 250, 500 and 750°C with account for microstructural evolution using X-ray diffraction (XRD) and scanning electron microscopy (SEM) to reveal the effect on thermal degradation and strength maintenance. It is shown that the addition of steel fibers can improve both ambient and residual mechanical properties, and a 1.0% fiber volume fraction has the best strength preservation behavior at all temperatures. However, the residual compressive, tensile and flexural strengths of fiber-reinforced GPC were much higher than that of the plain mix at different temperatures even if a decline with a raise in temperature was inevitable, especially at 750°C presence considerable values, microstructural studies verified that matrix densification is higher developed due to effective crack bridging and promoted interfacial bonding lead adding fibers is responsible for superior fire resistance. These results emphasize the potential of SFRC GPC as an elevated temperature structural fireproof and environmentally friendly building material.

Keyword: Geopolymer Concrete (GPC), steel fibers, elevated temperatures.

Introduction

Ordinary Portland cement (OPC) is the predominant inorganic cementitious material utilized in the contemporary building sector, and its manufacturing process may result in significant environmental contamination. The manufacture of one ton of OPC produces approximately one ton of carbon dioxide (CO2), with the OPC industry accounting for 5–7% of global CO2 releases [1]–[5]. To further promote environmentally conscious and sustainable development, it is essential to identify eco-friendly materials as substitutes for cement-based concrete. Geopolymer was a composite material formed by the interaction of solid industrial byproducts, including fly ash (FA) and ground granulated blast furnace slag (GGBS), which serve as cementitious ingredients, with alkali activators [6]–[8]. The manufacturing technique significantly diminishes energy usage and CO2 releases, establishing it as a novel material with substantial developmental potential [9]–[12]. In comparison to conventional concrete, geopolymer concrete (GPC) offers superior strength, enhanced fire resistance, and improved corrosion resistance [13]–[15]. Nonetheless, its shortcomings, including significant deformation, susceptibility to cracking, and brittleness, are critical considerations that restrict its extensive utilization [16].

Nevertheless, the GPC brittleness has lately led investigators to explore a diverse array of studies. The utilization of short fibers in GPC enhanced performance regarding fire resistance, shrinkage, and ductility [17], [18]. Fibers having a low melting point, like polypropylene [19], are more efficacious since they establish dehydration channels at reduced temperatures. Concrete spalling results from two primary variables: elevated pore pressure and the development of thermal stress [20]. Fibers, steel bars, and other fibrous materials have been utilized to mitigate cracking in concrete through the anti-tensile characteristics [21]. The materials have a thermal coefficient comparable to that of concrete [22]–[24]. The integration of fiber into concrete may markedly enhance its fracture resistance. Consequently, it improved various mechanical characteristics, including tensile, flexural, and impact strength, while simultaneously augmenting the ductility and toughness of the concrete components [25].

High temps influence the physical and mechanical characteristics of concrete. An elevation in temperatures induced by fire may result in irreversible degradation of concrete strength and a decrease in its cross-sectional area owing to the concrete cover spalling. GPC has favorable thermal features, with no spalling seen after exposure to fire [26]. Prior research has shown that GPC samples have superior compressive strength compared to OPC samples under both normal and heat curing conditions [27]–[29].

Exposure of concrete to elevated temperatures leads to spalling, defined as the detachment of surface layers, and external cracking, which occurs due to the evaporation of free water and the degradation of the paste. The events may subject the steel reinforcements inside the concrete to heat, potentially resulting in catastrophic consequences for the concrete structure stability and load-bearing capacity. Moreover, alkalinity decreases due to carbonation, exacerbated by fire, hence increasing the steel rebars corrosion risk [30], [31]. At temperatures above 400 degrees Celsius, the paste commences to contract while the aggregates grow, resulting in a pronounced strain gradient inside the matrix [32]. It

exacerbates cracking inside the matrix and diminishes the adhesion between aggregates and paste, leading to further deterioration of strength. At high temperatures, namely 800-1000 degree centigrade, the breakdown of products of hydration and the chemically-bound water loss cause considerable degradation of the microstructure, resulting in a 60-80% decrease in strength [33].

This study's main objective is to assess the impact of steel fiber volume fraction on mechanical properties and thermal resistance ability of geopolymer concrete mixed with a hybrid FA–GGBS–OPC binder after exposure to elevated temperatures (up to 750°C). The novelty lies in complementary residual compressive, tensile, and flexural behavior investigation alongside comprehensive microstructural analysis, establishing direct correlation between the evolution of geopolymeric phase, fiber-matrix bonding, and post-fire form-stability features. In contrast to the previous studies which have given single measures of either ambient performance or mechanical properties, this work provides a comprehensive thermo-mechanical and microstructural model of steel fibre benefits towards thermal damage resistance and fire resistance in geopolymer concrete.

1. Methodology

1.1 Material Utilized

In this study, Ordinary Portland Cement (OPC) Type I was used a reference binder in the production of geopolymer concrete (GPC), so as to ensure a fair comparison with typical cement based systems; this is universal type cement that being commonly employed for structural applications and its main chemical composition including CaO, SiO_2, Al_2O_3 etc., and physical properties (such as fineness and specific gravity) were analyzed according to the relevant standard test codes listed and presented in Tables 1 and 2. Ground Granulated Blast Furnace Slag (GGBS) [34], GGBS is a non-metallic and free-field by-product of pig iron production that mainly contains calcium silicates and aluminosilicates, the physical properties were described in Tables 1 and 2. Moreover, the Class Ffly ash used was a partial substitute for the cement [35], which complies with the relevant specification and is obtained from EUROBUILD, this being of fine particle size and pozzolanic nature with physical–chemical properties reported in Tables 1 and 2. where the alkaline activator consisted of a mixed aqueous solution of sodium silicate (Na_2SiO_3) and sodium hydroxide (23 wt.% NaOH), with reactivity controlled through the molar ratio of silica dioxide to sodium oxide (modulus SiO_2/Na_2O) which not only determined the Si_x^+ anion concentration in solution, but also affected by water content, leading to changes in viscosity and geopolymerization kinetics; sodium hydroxide was prepared from 99% purity flakes by dissolving them in distilled water to reach the desired molarity and then keeping cooling for at least two hours before usage; such practice makes sure of good stability. To improve workability without increasing the water demand a compliant with ASTM non-chloride high range water reducing superplasticizer, Sika® ViscoCrete®-5930 was added. The coarse aggregates tested for the research were natural river sand as shown in the standard specification, graded as Figure 1 and had a nominal maximum size of 12.5 mm [36], while the fine aggregates are natural river sand which had a maximum particle size of 4.75mm (Figure 2) and they met with the specified grading limit [37]. The tensile behavior of the GPC was also enhanced by the addition of hooked-end high-strength steel fibers with volume fractions ranging from 0% to 1% in increments of 0.5%, with an average diameter around 0.55 mm, a length of about 35 mm, and an aspect ratio of about 64, while its maximum tensile strength could reach up to 1345 MPa.

Table 1. Physical Features

No	Material	Specific Gravity	Specific surface area m^2/kg	Water Absorption %	Dry Loose Unit Weight kg/m^3	Sulfate amount (SO_3) (%)	Material passing through the 0.075 mm sieve
1	FA	2.44	521	-	-	-	-
2	GGBS	2.57	290	-	-	-	-
3	Cement	2.58	372	-	-	-	-
4	Coarse aggregate	2.69	-	1.11	1625	0.088	-
5	Fine aggregate	2.44	-	1.22	1798	0.074	1.84

Table 1. Oxide Composition of Cement, Fly Ash, and GGBS.

Oxides composition	Features		
	FA	GGBS	Cement
CaO	1.52	30.10	62.60
Al_2O_3	22.10	8.78	5.20
SiO_2	62.22	35.40	21.5
Fe_2O_3	7.12	1.97	3.40
MgO	2.34	6.92	2.42
SO_3	0.15	0.41	2.44
Loss of Ignition (L.O.I)	1.55	0.80	1.81

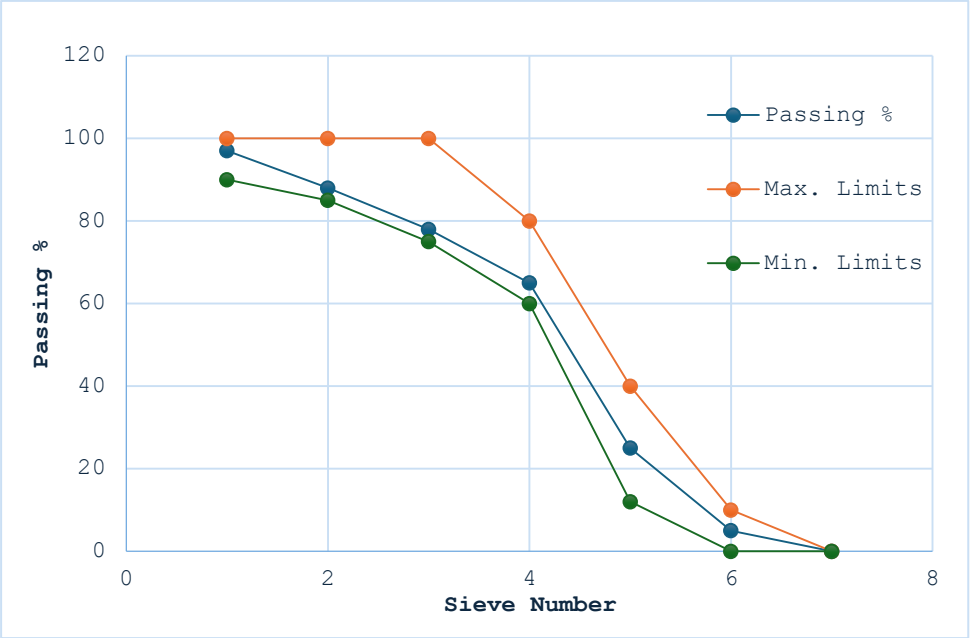

Fig. 7. - Figure 1. Particle size distribution of coarse aggregate.

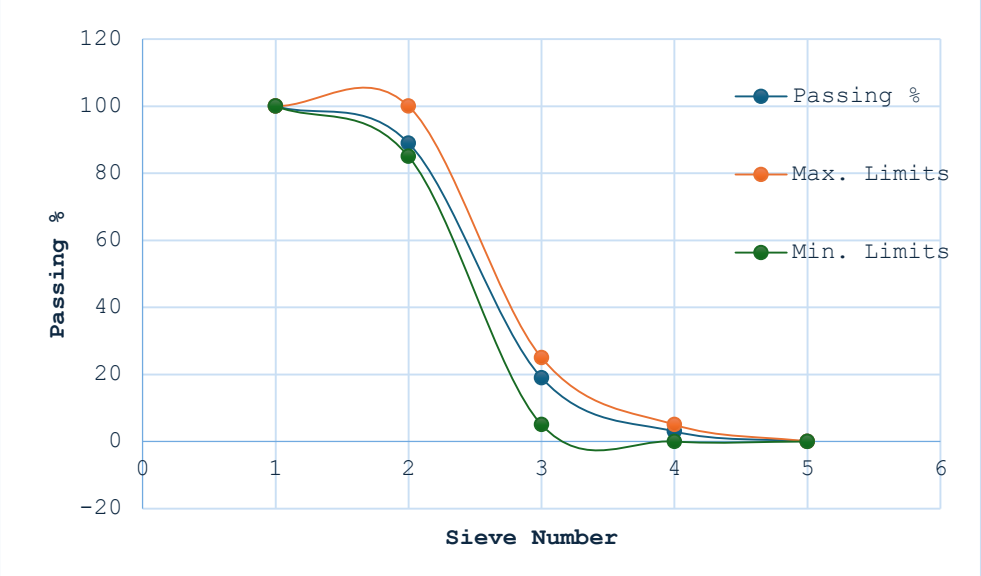

Fig. 8. - Particle size distribution of fine aggregate.

1.2 Mixture of Designations

Geopolymer mortar mix design and preparation following existing practice was defined according to references [38] as well as other standard procedures, considering test mixes handled at the age of 28 days demonstrating that selected mix formulation led to good compromise between workability and mechanical strength. A fixed alkaline activator–to–binder ratio of 0.40 was taken, which is well known to stimulate dense geopolymer gel formation and improved strength development, whereas a sodium silicate to sodium hydroxide ratio of 2.5 was kept for activity and reaction kinetics [38]. The geopolymeric binder system used a mix design that included 50% of GGBS, 40% of Class F fly ash, and 10% of ordinary Portland cement, which allowed obtaining an optimum combination for alkaline activated calcium- and aluminosilicate-rich precursors. The alkaline activator was formulated with constant sodium silicate and sodium hydroxide contents to keep consistency among all combinations. The natural fine and coarse aggregates were added at fixed contents, so that the influence of aggregate effect on other performances is excluded. To study the effect of fibre reinforcement on the properties of the geopolymer, hooked-end steel fibre was incorporated at volumetric proportion 0%, 0.5%, 0.75% and 1.0%. The general mechanism of geopolymerization and the stepwise order of materials reacting after mixing and curing are schematically depicted in Figure 3.

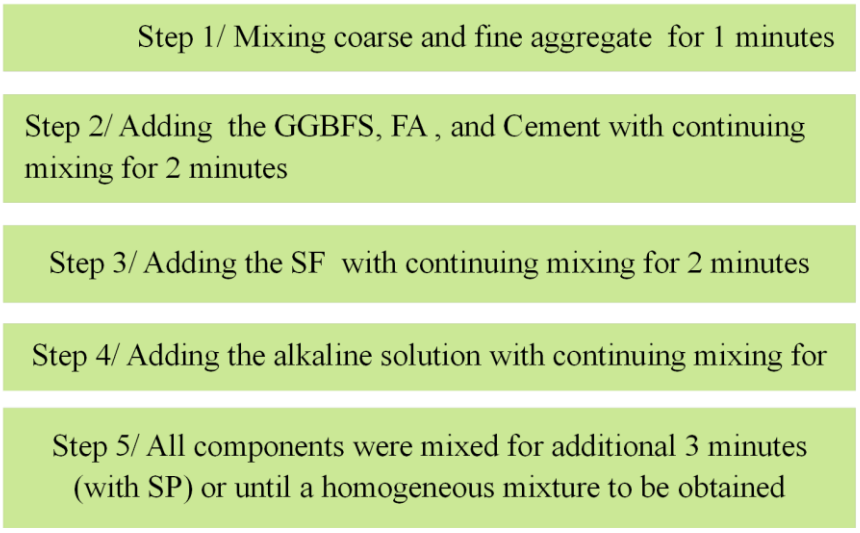

Fig. 9. - Flow chart of GPC mixing procedure steps.

1.3 Tests

X-Ray Diffraction (XRD) analysis

XRD analysis was employed to examine the phase composition and crystallinity of geopolymer cubes comprising 40% fly ash, 50% GGBS, and 10% OPC, treated to different temperature exposures (25, 250°C, 500°C, and 750°C). This approach facilitated the detection of crystalline phases and any phase changes induced by increased temperatures. XRD analysis of diffraction patterns yielded essential insights into the alterations in the geopolymer matrix structure, facilitating the evaluation of stability, the production of new compounds, and the thermal behavior of the material under varying temperature exposures.

Scanning Electron Microscope (SEM)

SEM analysis was performed to investigate the microstructure of heat treated Geopolymer cubes were prepared using 40% fly ash, 50% GGBS and 10% OPC. SEM provided high-resolution images for the assessment of changes in surface morphology and material integrity at various temperatures (25°C, 250°C, 500°C, 750°C). The findings showed the fissure growth, particle packing and structural densification under temperature dependence were plotted against the temperature, providing critical information on the thermal stability, bonding behavior under burning conditions and probable transition corresponding to phase change in geopolymer structure at elevated temperature.

Mechanical Behavior

Mechanical characterization of the geopolymer concrete mixes was performed through a full testing program under ambient temperature (25 °C) and exposure to elevated temperatures (250 °C, 500 °C, and 750 °C) to compare initial versus residual properties. All tests were conducted according to widely regarded ASTM standards to be able to make results repeatable and comparable with ordinary cement-based systems. Compressive strength was measured in cube specimens submitted to uniaxial compression according to the (ASTM C109/C109M) [39]. The splitting tensile strength was tested to indicate the crack resistance and tensile behavior with a cylindrical specimen according to ASTM C496/C496M [40]. Bending strength (modulus of rupture) was evaluated on prismatic specimens loaded in three-point bending, according to ASTM C78/C78M [41].

2 Results and discussion

3

2.1X-ray Diffraction (XRD) analysis

Figure 4 shows the X-ray Diffraction (XRD) of the GPC samples for various curing temperatures (25 °C, 250°C, 500°C and 750°C) which exhibits clear structural transformation. At (25 C°) the XRD pattern shows that an amorphous and crystalline phase mixture obtained in unfired brick, with aluminosilicate gel as a binding matrix reinforced by crystalline fillers as quartz and mullite, together contribute to strength enhancement from hydration products of GGBS such as C-S-Hand C-A-S-H. At 250°C the higher temperature accelerates the geopolymerization process, as a more compact gel and developed crystalline phase that can intensified strength emerged. At 500 °C, a reduction in amorphous phase and increase crystalline phase contribute to better material densification and higher thermal resistance. At 750 °C, formation of an intense crystallinity appears in the structure of GPC with less amorphous phase formed which refers to more completion geopolymerization and considerable content of thermally stable compounds [42]. It reveals that the higher curing temperatures can enhance not only mechanical strength but also thermal stability, thereby facilitating the use of formulations in civil engineering, such as flame-resistant structures as well as high-temperature industry. The variation of temperature had little effect on the XRD patterns of the materials, because the main crystalline phases (quartz (SiO_2), mullite ($Al_6Si_2O_{13}$) from fly ash and hydration products such as calcium silicate hydrate C-H-S and calcium aluminosilicate hydrate C-A-S-H from GGBS are thermally stable within 250-750°C which is examined in this study. Therefore having higher melting point, makes them resistant to phase transition at moderate to high heating conditions [43]. The amorphous phase (the majority of which is aluminosilicate gel) does not significantly change its presence throughout the temperature

regime. While an increase in temperature leads to a shorter geopolymerization reaction time and decreases amorphous content, the main phase also remains the same and therefore diffraction patterns were similar. Since the crystalline components are stable overall and the amorphous phase fairly gradually decreases, no significant change is detected in XRD patterns even with temperature variation [44].

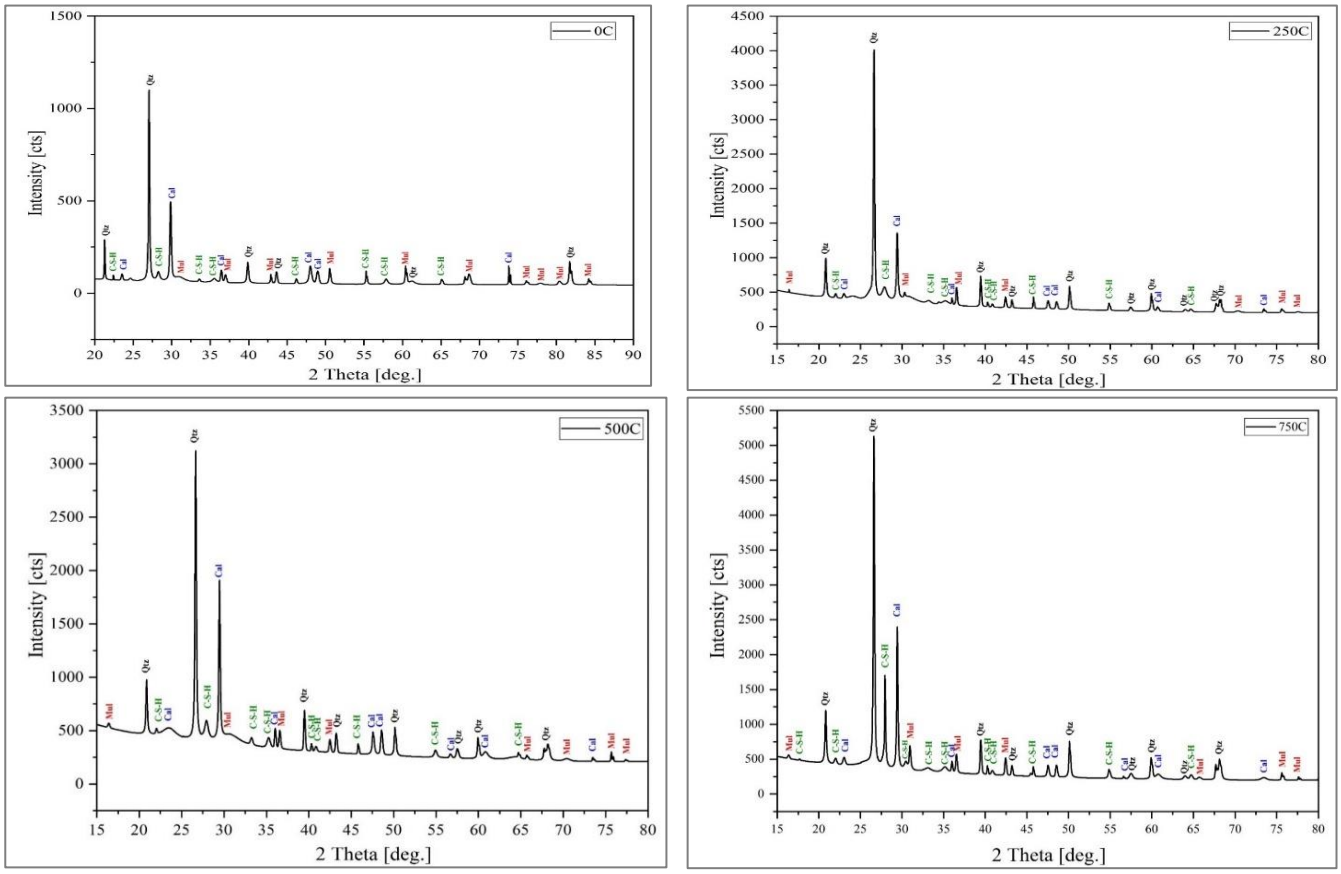

Fig. 10. - XRD pattern for GPC at (25, 250, 500 and 750) °C.

2.2 Scanning Electrons Microscopy (SEM)

The SEM image of GPC with 25°C is illustrated in Fig.5. Here, at lower temperature polycondensation will be slow and there will be little development of binding aluminosilicate gel. The poorly defined matrix in this image shows only incomplete coating of unreacted particles by the gel, resulting in visible porosity and a rough surface texture. Early-age ettringite, a needle-shaped calcium sulfoaluminate hydrate, may exist due to the interaction of GGBS with sulfate. This reaction is passive due to the low temperature and cannot have sufficient role in matrix densification. Increased curing temperatures are necessary to accelerate the disintegration of aluminosilicate components from fly ash and GGBS that eventually assist in developing a compact, cohesive matrix improving mechanical properties. The limited quantity of poor development of the geopolymer gel at 25 °C is a result of the slow kinetics associated with the geopolymerization shown in Figure 5. On cooling, the dissociation of aluminosilicate materials in fly ash and GGBS is severely retarded, which reduces the exposure of reactive species required for gel precipitation. Partial reaction leads to non-reacted spherical fly ash and angular GGBS particles in the matrix, giving rise to porous network. The formation of ettringite is retarded and reduced at low temperatures since calcium, aluminum and sulfate ions are required for the formation of that mineral. GGBS could present these components, though low-temperature limitation of crystalline is not permitted. The microstructure shown in the figure is of a weakly cemented complex and underdeveloped geopolymers system typical for curing at low temperature.

The SEM image of the GPC that has been exposed to 250°C, on the other hand, shows a significant improvement in matrix densification (Figure 6). Elevated temperatures accelerate the process of geopolymerization with increased formation of a denser aluminosilicate gel which can connect more favorably to aggregate particles. The image shows lower porosity, more coalescing structure, and smoother region indicating better adhesion between the particles. Although it is possible that some unreacted fly ash and partly reacted GGBS particles still exist, bulk structure appears more bonded due to enhanced reactivity of the material at this temperature. The stronger bonding results in better mechanical properties, making the geopolymer concrete suitable for structural applications where high strength and long-term durability are required.

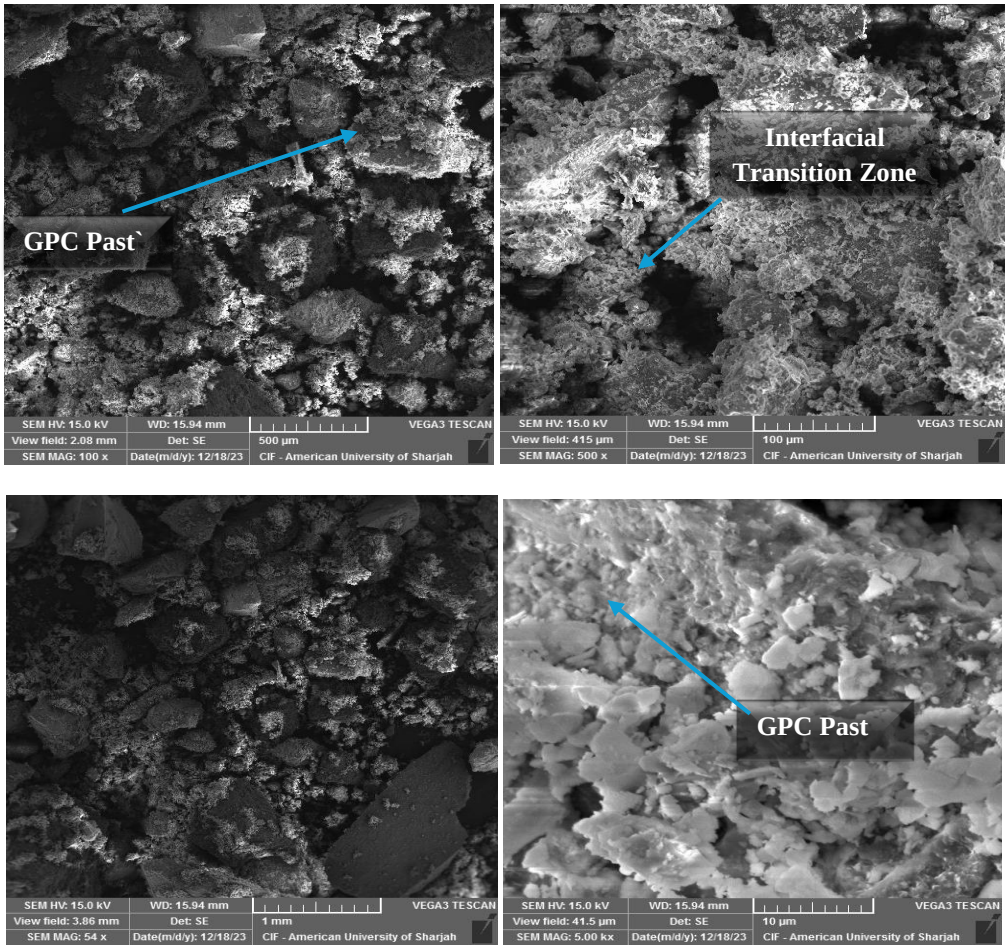

Fig. 11. - SEM image for GPC sample at (25 °C).

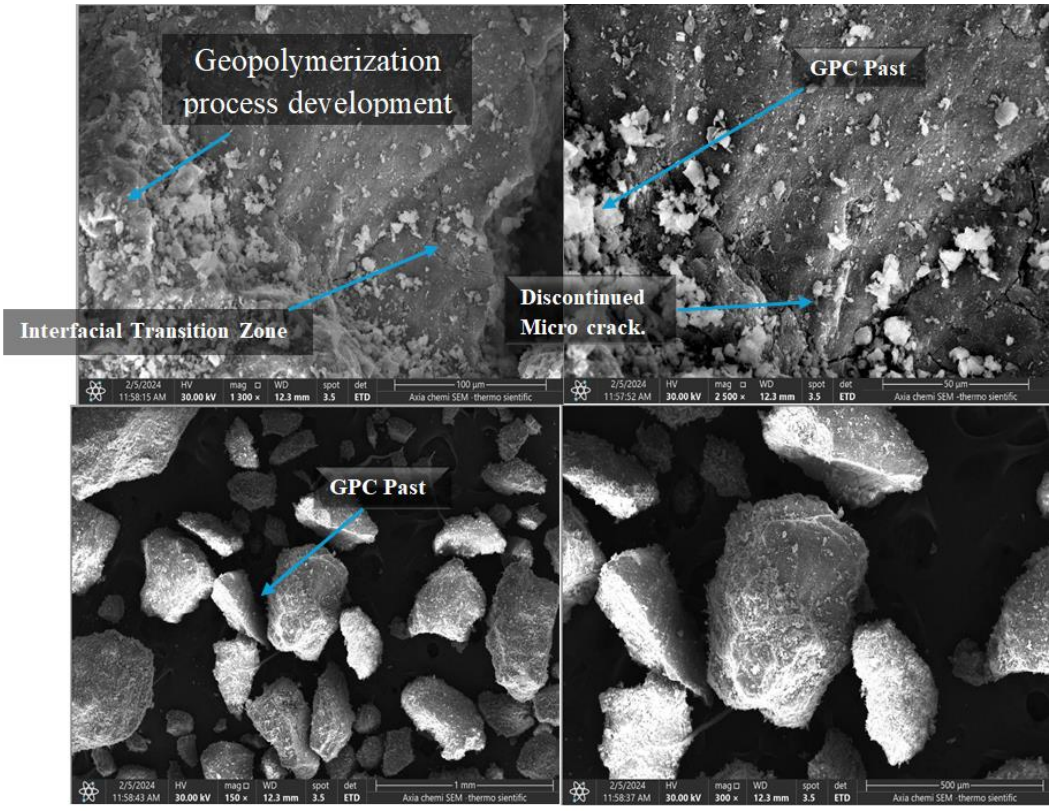

Fig. 12. - SEM image for GPC sample at 250 °C.

Figure 7 shows the SEM image of at 500°C, which reveals a dense and well-bonded matrix with zero visible porosity. The higher temperature itself leads to a more rapid geopolymerization process whereby a dense aluminosilicate network is formed with rougher surface topography, indicating crystallite growth. The presence of C-S-H and C-A-S-H in the matrix enhances its strength, while the coarse- grained appearance suggests that crystallization of these phases is ongoing. Superior microstructure resulting in enhanced mechanical strength and resistance to attack from the environment which is lowered more porosity making GPC 'most suitable for elevated temperature and civil structural applications.

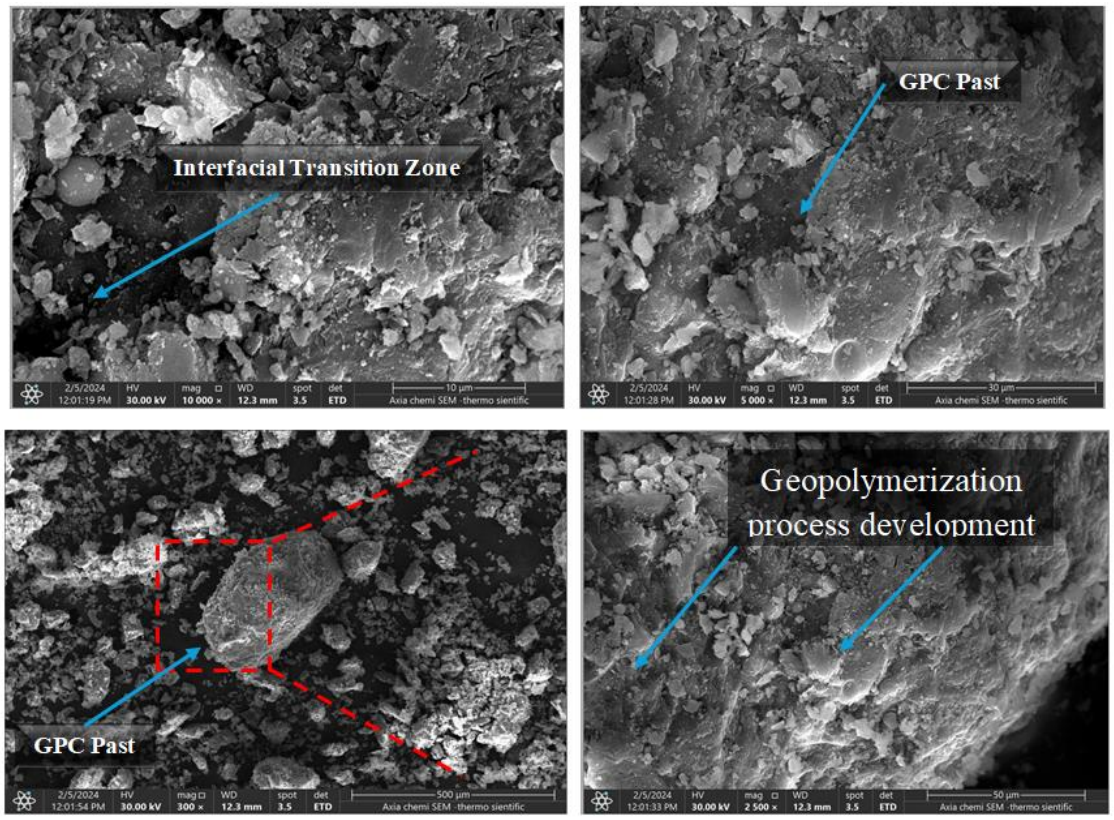

Fig. 13. - SEM image for GPC sample at 500 °C.

The SEM images of the GPC cured at 750°C are displayed in Fig. 8, and its microstructure is a densely packed crystalline structure with sharp-edged particles. The increase in temperature also accelerates geopolymerization and crystallization with a less porous and stronger matrix. The presence of crystalline phases, C-S-H and C-A-S-H, results in good structural improvement, and the remaining fly ash acts as fillers. The surface pattern formed by the broken, namely open, enables heat resistance and dent resistance of the material. The microstructure variation at 750°C makes GC a suitable choice for high performance applications requiring sustainable, thermal, and mechanical properties such as fire resistive construction. The compressive strength of the GPC decreases dramatically with increase in burning temperature. Upon the burning temperature increasing from 25°C to 250°C, the compressive strength is reduced by a half. This significant reduction is attributed to the influence of temperature on the microstructure of the material, where insufficient geopolymerization occurs at lower temperatures and results in an immature binding matrix. The limited interaction between fly ash and GGBS leads to inferior mechanical performance. With the increase in temperature in the chamber to 500°C, layer C loses further 51% of its original compressive strength at 25°C The continuous weakening is due to faster reactions at higher temperatures, leading to dissolution of aluminosilicate components from fly ash and GGBS into a dense matrix but with possible micro-cracking and phase transformations that weaken the material. The SEM analysis at this level shows increased gelation but the general structure is still deteriorating. At elevated temperature of 750°C, the strength is about 70% lower than that at 25°C; higher temperatures favor crystallization with the appearance of crystalline phases comprising calcium silicate hydrate (C-S-H) and calcium aluminosilicate hydrate (C-A-S-H), as shown in the microstructure. However, the excessive crystallinity and potential thermal decomposition makes for a tailorable brittle matrix with poor crush resistance. Despite of the densification, the decrease in mechanical strength makes it less applicable for load–bearing application at elevated temperatures.

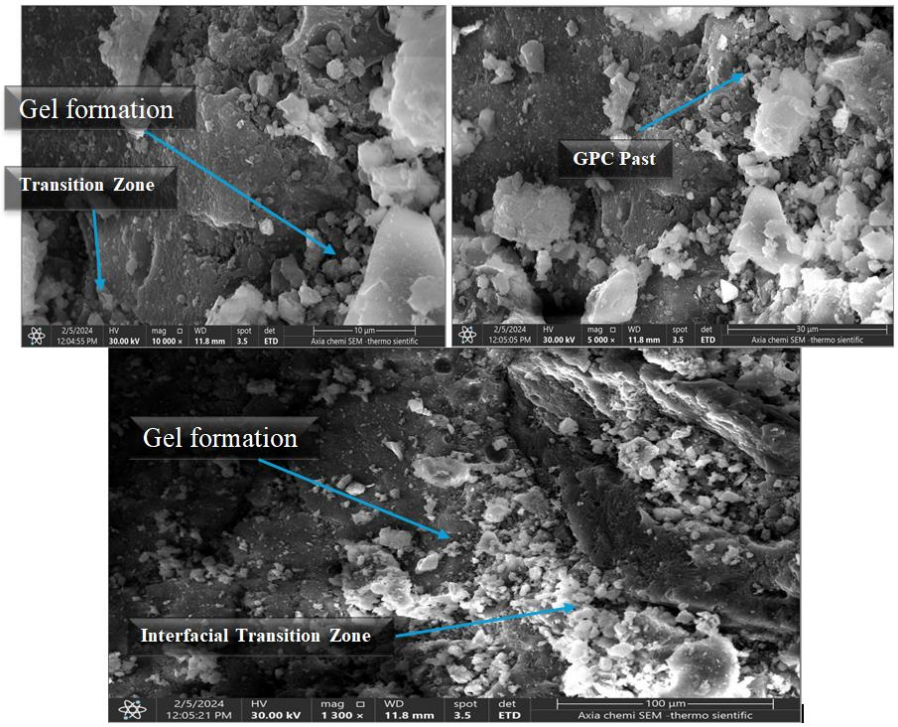

Fig. 14. - SEM image for GPC sample at 750 °C

2.3 Compressive strength

Steel fiber reinforced GPC samples showed higher compressive strength in cube samples compared to those without fibers. The compressive strength increased by 21%, 35% and 59% for S2, S3 and S4 with the addition ratios of steel fibers being 0.5%, 0.75% and 1.0%. Compressive Strength of the Fiber Concrete The use of steel fibers enhanced the compressive strength, with a maximum value being 59 MPa at a fiber ratio of 1.0%, which is approximately consistent to results shown in [45]. The smallest compressive strength for the fiber-reinforced specimens was 40.5 MPa for mix S2 (0.5% of steel fiber), higher than the value obtained in the GPC without steel fibers (38.9 MPa). Residual compressive strength of the steel fiber-reinforced geopolymer concrete mixes subjected to elevated temperatures is shown in figure 9, as compared with those under ambient condition. Addition of steel fibers significantly prepared an improvement in retention of strength at elevated temperature. With the increasing of fiber content, strength decay rate decreased, and higher in volume fractions fibers showed better thermal resistance and remain larger portion of initial strength. At 250°C, there was an increase in the residual strength compared to that at lower volume fraction of fiber, which may be attributed to improved interaction between steel fibers and geopolymer matrix by further polymerization as well as microstructural densification. At room temperature, the compression strength rose from 38.9 MPa (plain mix—S1) to 59 MPa (1%-fiber mix—S4), offering an improvement of around 52%. FRM outperformed SM at higher temperatures. At 750 °C, the strength of S4 (27 MPa) remained more than double that of S1 (12.01 MPa). Similar increases were also recorded at 250°C (from 30.1 MPa to 43.3 MPa) and at 500°C (from 21.3 MPa to 32 MPa). The findings show that both ambient and residual compressive strength increase with an increasing steel fiber content, in which the 1.0% steel fiber results in the largest rate of improvement under all conditions.

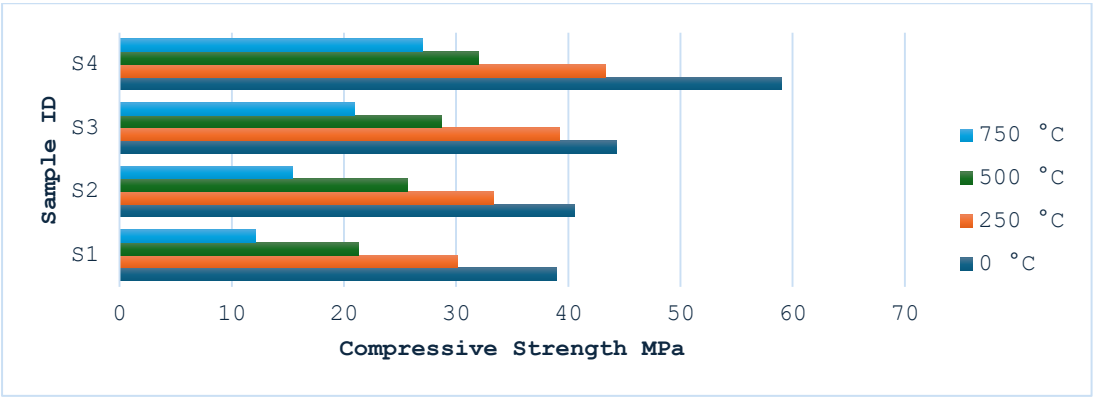

Fig. 15. - Compressive strength for different GPC mixture subject to various temperature

2.4 Tensile strength

As shown in Figure 10, the tensile strength of all samples has also decreased with increasing temperature and exhibits a similar behavior to that observed for the compressive results. Control sample S1 showed tensile forces of 1.89 MPa, 1.4 MPa, and 1.1 MPa at temperatures of 250°C, 500°C and 750°C respectively which are decreased by the value of14%, 36% and 50%. 0.5% by weight steel fibers (S2) addition led to 2.78 MPa, 2.5 MPa and 1.5 MPa of residual tensile strengths, showing loss reduction of 14%, 22% and 53 %, respectively. S3 mixture also showed even further improvement showing a decrement in tensile strength by only 10%, 23% and 28%. Sample S4 showed the best residual compressive strength of 26%, 31%, and 40% at temperatures of 250°C, 500°C, and 750°C, respectively. The tensile strength decreased as the exposure temperature increased. At 250°C, tensile strength increased by 47%, 95%, and 117% for S2 (0.5% SF), S3 (0.75% SF), and S4 (1.0% SF) when compared to S1 (SRM) which demonstrated a similar trend to that of compressive strength. The residual tensile strengths corresponding to the grains layer above 500 °C were 1.4 MPa (S1), 2.5 MPa (S2), 3.16 MPa (S3) and 3.78 MPa (S4), augmenting by of an average value of de un valor medio del 79%, 125% and for SFRM, respectively. The reduced strength of S1 is attributed to the partial deterioration and dehydration mechanism of calcium-aluminosilicate hydrate (C-A-S-H), which could not be supported by an inadequate amount of water for reaction. Ctrl R 0 S1 S2 S3 S4 Resistivities Room temperature Effect of fiber content on the tensile strength The composite fibers all have the same diameter, thus having similar surfaces. The highest value of residual tensile strength (3.3 MPa) was obtained at 1.0% steel fiber, which confirmed the positive role of fiber proportion to temperatures. The tensile strength of GPC decreases with temperature, but by the inclusion of steel fibers its fire resistance is significantly improved. At room temperature, obviously, the strength increases with the content of fibers from 2.2 MPa (0% SF) to 5.51 MPa (1.0% SF). All the mixtures show strength reduction when temperature increases to 250, 500 and 750 °C, however the fiber-reinforced specimens have higher values. At 750°C, it reported a maximum strength of 3.3 MPa for the 1.0% SF mixture which is greater than that obtained from the control sample (1.1 MPa).

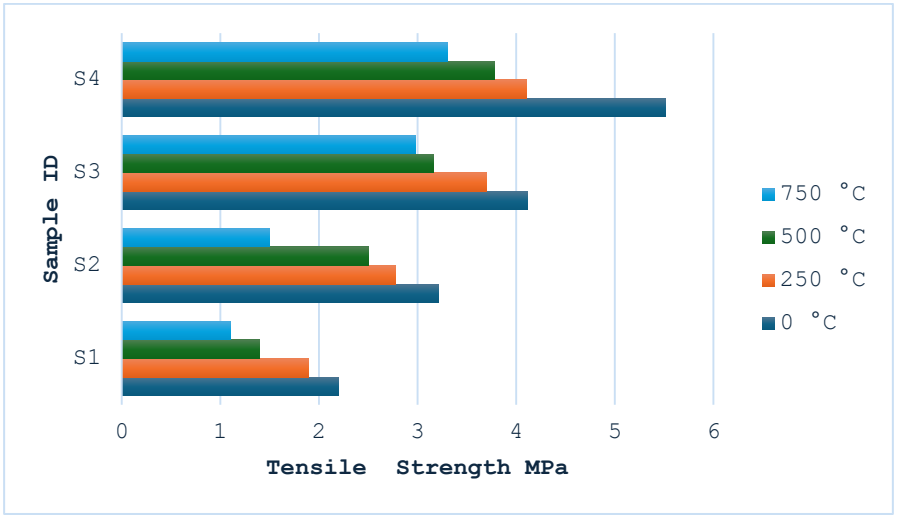

Fig. 16. - Tensile strength for different GPC mixture subject to various temperature

2.5 Flexural Strength

The variation of the flexural strength at elevated temperatures for GPC specimens is illustrated in Figure 11. The loss of strength increases specifically with the temperature when considering all the steel fiber contents. The flexural strength of the control sample (S1) decreases by 14% at 250°C as compared to that at room temperature. The flexural strengths of GPC specimens significantly decreased after exposure to fire, especially at 500°C–750°C; the residual flexural strength was reduced to 66% (S1), and 60%, 41%, and 38% (S2, S3, and S4) at 500 °C. At 750°C, the retained strength was 87% for S1 whereas it decreased to approximately 73%,,71%, and 69% for S2, s3, and S4, respectively. Despite the overall decline, mixtures with steel fibre (S2–S4) showed to continue outperforming the fibre-free mixture (S1) at all exposure levels. This is in accordance with the obtained enhancement of compressive and split tensile strengths. S2 reached the flexural strengths as 5.14, 2.2 and 1.5 MPa after being subjected to temperatures of 250,500 and750°C, respectively. The residual flexural strengths of S2 were 14, 24 and 117% at these temperatures as compared to the pristine GPC (G1-0%SF), while those of S3 were 34, 111 and 168%, and those of S4 were found to be enhanced by 40,137 and 204%, respectively. The findings of the results clearly demonstrate that elevated temperature drastically reduces the flexural strength of all GPC mixes. The amount of reductions is dependent upon the ratio of steel fiber. The control mix with no fiber content (S1) has higher degradation, where the flexural strength drop from ambient temperature 5.25 MPa to 0.69 MPa at only 750 °C, while fiber incorporated concrete of all (S2, S3 and S4) possess larger residual strengths at all temperatures. S4 shows an excellent applicability, maintaining the flexural strength of 2.1 MPa at 750 °C, which is three-fold higher than that of unmodified mixture. This indicates that the heat resistance and structural performance of GPC in fire are enhanced by increasing the steel fiber content. The positive role of steel fibers is due to their ability to control the

crack and improve matrix binding at elevated temperature, in particular. The results confirm that the usage of steel fiber can effectively improve the high-temperature properties of GPC, thereby avoiding its reduced reliability in applications requiring better fire resistance.

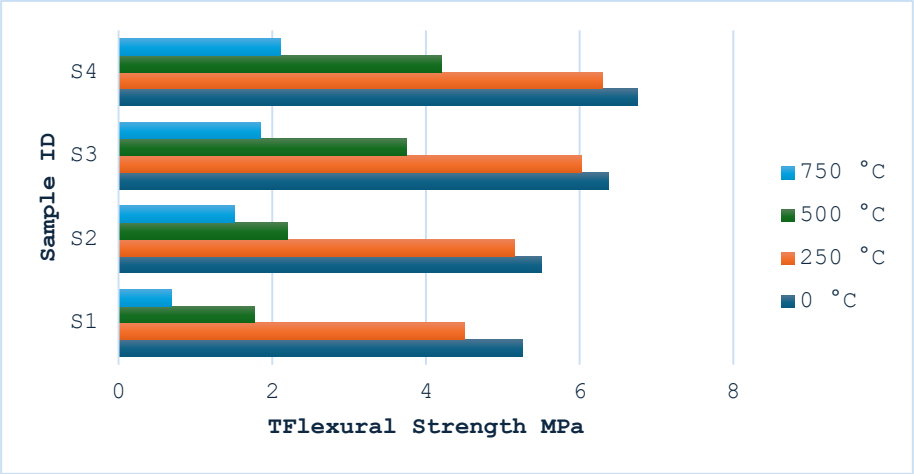

Fig. 17. - Flexural strength for different GPC mixture subject to various temperatures

Conclusion

The results of the experiments conducted demonstrate the importance of reinforcing with steel fibers in acting as an essential element to enhance the thermal mechanical performance of geopolymer concrete at micro and macro level temperatures. It was observed that the use of hooked end steel fibers largely increased compressive, split tensile and flexural strengths, where fiber content of 1.0% has resulting in the highest increments with continues strength retention after thermal attack. At high temperatures, fiber-reinforced GPC achieved significantly higher compressive and tensile residual strengths compared to the plain mix with more than double that exhibited at 750°C whereas plain GPC only showed an increase over 400°C.334 Higher temperature resulted in more geopolymerization gel formation and matrix densification up to intermediate temperatures along with steel fibers acting as a bridge to connect thermally induced microcracks were effectively bonded by steel fibers, increasing bond between fiber/matrix and moving ITZ interface. Even if the fiber-reinforced mixes showed strength loss because of dehydration, crystallization, and microstructure damage at elevated temperature, they were still better than plain cement paste in resisting thermal erosion. In general, this study has shown an SFRGPC to be a viable and durable sustainable fire-resistant material, which is highly potential for load-bearing applications in elevated temperature or fire hazard environments.

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