Fire Resistance Performance of Fiber Reinforced Geopolymer Concrete: Review

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Abstract: Geopolymer is a relatively new substance that has sparked a surge of research into nearly every field of geopolymers in recent years. It's still on the verge of becoming a competitive OPC concrete alternative. Mechanical, hardness, and fire resistance properties of geopolymer are exceptional. There has been no/limited research on the effect of fiber integration on fire resistance of geopolymer concrete. In fire-exposed concrete, fiber can help to resist spalling. The goal of this study is to develop materials that exhibit eco-friendly properties and better fire-resistant behavior. Moreover, the combined effect of binder materials and different fibers on the fire resistance of geopolymer concretes. According to the findings, the fire resistance of fiber-reinforced geopolymer concretes increased in the order of carbon fiber-based GPC, micro-steel fiber-based GPC, hooked steel fiber-based GPC, and polypropylene fiber-based GPC. Furthermore, as compared to slag and metakaolin-based GPC, fly ash-based GPC has greater stability and fire resistance. Fiber-reinforced GPC can also be used as a sustainable and durable building material in various construction applications where high performance is needed.

Keywords: Geopolymers; fiber reinforcement; fire resistance; binder materials of geopolymer concrete.

Introduction:

Concrete and steel are the most commonly used construction materials in the world. Concrete is weak in tension, and it cracks at a low level of stress [1]. The concrete weak point is low tensile strength. Therefore, different repair and other materials were used to address the lack of enough tensile strength [1,2]. Geopolymer technology has recently been mentioned as the desire to replace conventional concrete (OPC) without cement [3,4]. Furthermore, the extreme utilization of cement is unacceptable, particularly when environmental considerations are taken into account. Mineral fillers or byproduct cementitious materials like silica fume, ground granulated blast furnace slag (GGBFS), metakaolin (MK), and fly the researchers utilized ash (FA). These materials are used to eliminate concrete costs while also improving its workability, flowability, and mechanical performance [5,6]. GGBFS and FA contribute to the performance of concrete and the economy and environmentally sustainable materials [7,8].

However, the brittleness of GPC has prompted researchers recently to a wide range of their researchers. It was indicated that the use of short fibers in GPC improved the performance in terms of better ductility, shrinkage, and fire resistance [9,10]. Fibers with a low melting point, such a polypropylene [11], are most effective as they create dehydration pathways at lower temperatures. Concrete spalling is caused by two significant factors: increasing pore pressure and thermal stress formation [12]. Steel bars, fibers, and other fibrous products are used to restrain concrete cracking via their anti-tensile properties. Especially the materials exhibit a thermal coefficient similar to that of concrete [13]. The incorporation of fiber into concrete can significantly improve the crack resistance of concrete. As a result, it enhanced the other mechanical properties, such as impact, flexural, and tensile strength, despite increasing the concrete members' toughness and ductility [14].

One of the reasons that contribute to concrete popularity is its relative fire resistance compared to steel structures and non-combustible materials, which exhibit cracking, spalling, poor thermal conductivity, and lack of mechanical properties. This is a significant concern, particularly for high-strength concrete [15]. Fire resistance of conventional concrete should be carefully examined, especially for concrete lining tunnels. Tunnels are exposed to severe fire conditions, as summarized in Table 1. Some researchers reported that fires in tunnels, resulting in the loss of life and property [16]. In the case of a tunnel explosion, the ambient temperature rapidly increases, allowing concrete to spall and the tunnel lining to cause substantial damage. Both firefighters and tunnel users are placed at risk. The costs suffered as a result of tunnel repair and tunnel closure is seen in Table 1. As a result, tunnel concrete must be checked for fire resistance. The temperature-time curve has been applied in ISO and RWS normal curves and the hydrocarbon fire curve for various tunnel fire testing rules.

Table 1. A brief survey of tunnel fire damages in the past years [16].

Year	Tunnel	Number of causalities	Loss of revenue M€*	Repair cost M€*
2006	Viamal	9 deaths	Not available	Not available
2005	Frejuas	2 deaths	3	2
2001	Set Cathard	11 deaths	Not available	Not available
1999	Tauem	12 deaths	20	8.5
1999	Mont blanc	41 deaths	203	189
1996	Eurotunnel Channel	2 injuries	203	49

*M€ presents the million euros.

Concrete can be protected from fires by using thermal barriers. However, this strategy to fire protection increases the cost of concrete. Furthermore, it degrades concrete hydration compounds such as calcium hydroxide, calcium silicate hydrate, and calcium carbonate when exposed to elevated temperatures. This should be avoided to prevent deterioration of the concrete microstructure [17]. Therefore, it is essential to develop a material that exhibits eco-friendly characteristics in addition to both fire and mechanically efficient, particularly for concrete structures that are exposed to fire or high temperatures.

Fire Resistance of Geopolymer Concrete

Geopolymers exhibit better fire resistance than ordinary Portland cement concrete. This may be attributed to the microstructure pore structure of geopolymerization materials. At the same time, water is not a component of the chemical composition of geopolymerization materials. In comparison to ordinary Portland cement concrete, hydrated cement requires water, and as a result, high temperature created, calcium silicate hydrate C-S-H decomposes, resulting in a substantial loss of mechanical ability [18]. Geopolymer concrete outperforms ordinary Portland cement concrete in fire resistance, meaning geopolymer concrete can be used in fire sites. Geopolymers are new building materials that can be used alternative to conventional Portland cement. Alkali bonded ceramic, mineral polymer, inorganic polymer glass, and alkali-activated cement are used to describe geopolymers [19]. In 1978, Davidovits was the first to coin the word "geopolymer"[19]. The binder materials of geopolymer concrete containing aluminosilicate compounds. Fly ash, ground granulated blast furnace slag, and metakaolin are examples of aluminosilicate compounds. Geopolymer products emit less carbon dioxide compared to Portland cement concrete [20]. Byproduct waste fly ash as a raw material in geopolymer poses environmental issues [20].

The process by which geopolymers achieve strength and harden is entirely different from that of OPC. Geopolymers can withstand compressive strength up to 100 MPa [19]. Geopolymer has excellent fire resistance, acid resistance, and alkali-silica reaction properties. It's also inorganic, non-toxic, and doesn't catch fire or emit pollution. On the other hand, geopolymers utilize fewer resources during the production process [19]. Many variables influence geopolymers' microstructure stability after temperature prompts thermal expansion, which contributes to macro cracks. Controlling mesoscale thermal deformation is greatly improved by optimizing the water content of geopolymers. Heating, including the alkaline type, cation, and Si/Al ratio of the source material [21].
Metakaolin geopolymers were found to be unsuitable for use as a building material subjected to fire. Complete alkalinity content in geopolymers has a direct effect on mechanical efficiency at the room, and elevated temperatures, so maximizing alkalinity content in geopolymers is essential [22] The effect of NaOH solution concentration on thermal and mechanical efficiency was investigated. It was concluded that increasing the NaOH solution concentration from 10M to 16M reduces strength loss after heat exposure at 800 ºC [23]. The effect of the Si/Al ratio in fly ash base geopolymers was investigated. After exposed to 1000 ºC, it was discovered that decreasing the percentage of Si/Al contributes to improve the fire resistance. It was also found that the addition of inorganic fillers such as alumina minimized shrinkage at high temperatures.

According to the researcher, geopolymer composites' fire resistance must be investigated at the micro, meso, and macro levels before they can be used as a fire-resistant building and construction material [21]. Many researchers found that when geopolymers were subjected to high temperatures, they remained stable [24]. The fire resistance of geopolymers was developed using metakaolin as the base material and sodium silicate as the alkali activator; it was indicated that geopolymers exhibited substantial thermal stability [25]. It was evaluated that increasing the initial alkalinity of geopolymers increases fire tolerance [26] It was concluded that exposing metakaolin geopolymer to high temperatures results in the formation of the crystalline phase. It was also explained that, regardless of alkaline form, the crystalline phase volume decreases with the reduction of the Si/Al ratio. Simultaneously, the heating rate of geopolymers influences both thermal shrinkage and phase composition [27]. After calcining at 1000ºC for 1 hour, there was no difference in the geopolymers' amorphous composition [27]. After exposed to high temperatures, metakaolin-based geopolymers developed a crystalline structure.

The effect of elevated temperature on slag/fly ash-based geopolymers mortar [28]. It was recorded that increasing the temperature to 400, 600, and 800ºC for three hours reduced traditional mortar's mechanical properties, resulting in flexural strength losses of 20, 50, and 70%, respectively. Compressive strength was reduced by 25, 45, and 65 percent, respectively. Mechanical properties of slag-based geopolymer mortar, with compressive strength losses of 15, 20, and 30%. When exposed to 400 and 600 degrees Celsius, a fly ash/ slag (50/50) geopolymer mortar's mechanical properties were improved, resulting in increased flexural resistance. When exposed to 800C, however, the power was reduced by 32% [28]. The study showed that increasing the substitution of fly ash with slag improved fire tolerance. The fire resistance of a geopolymer paste made from fly ash was tested [29]. They reported that increasing temperature from 100-1100ºC steadily falls down the compressive strength [29]. The ambient/heat-cured GPC was investigated [30]. The ambient cured GPC had a lower loss of strength (27%) than the heat-cured geopolymers concrete, which had a (50%) loss of strength [30]. The thermal activity of geopolymers and geopolymer/aggregate composites was studied [31]. The strength of a fly ash-based geopolymer/aggregate composite weakened when subjected to elevated temperatures due to differential thermal expansion of the geopolymers and aggregate.

Binders Based Geopolymer Concretes

Geopolymers are created by reacting aluminosilicate materials with alkali activators. Aluminosilicate compounds have a high concentration of silica and alumina in their chemical composition. They are also known as preliminary materials and forerunners. Natural materials such as metakaolin and clay minerals are used as base materials. Fly ash, ground granulated blast furnace slag, and silica fume are among the industrial waste products also used as binder-based materials. In some cases, agricultural waste is often used as a geopolymer base material. Geopolymer composites are considered renewable materials because they consume fewer resources during the manufacturing process and positively affect the atmosphere due to co-polymerization [32]. Engineers in both fields are concerned about the environment's sustainability. Geopolymers have also been developed to create an environmentally friendly material and reduce the use of natural resources.

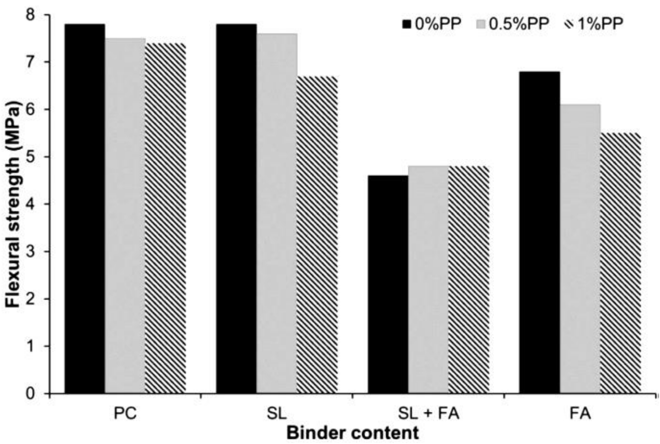


Figure 1. Effect of binder content and PP dosage on compressive strength [33].

Previous researchers examined the GPC with different binders, slag, slag/fly ash and fly ash mixes and discovered that compressive strengths improved in the order of FA-based GPC, FA/GGBFS mixture-based GPC, and GGBFS based GPC. The researchers then looked at the XRD patterns of FA-based GPC (100% FA) to see the impact of low calcium fly ash. Less reactive calcium (Ca) resulted in less calcium-silicate-hydrate (C-S-H), and the lower volume of Ca in the FA did not contribute in the production of calcium-silicate-hydrate, explaining the poor mechanical strength of FAGPC specimens. They also discovered that the key hydration agent for FA-based GPC specimens is calcium aluminum oxide hydroxide hydrate ($Ca_6Al_2O_6(OH)_.2H_2O$) [6, 34]. Table 2 illustrates the properties of binder-based geopolymer concretes.

Table 2. The properties of FA, GGBFS, MK and PC [35-37].

Component	**CaO**	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**SO_3**	**K_2O**	**Na_2O**	**LOI**	**SG**	**BF (m^2/g)**
MK (%)	0.10	43.6	51.4	1.4	0.10	-	0.20	-	-	2.60	18000
PC (%)	65.58	20.825	5.31	4.04	2.82	2.73	0.92	0.22	3.02	3.15	3260
FA-F (%)	1.59	62.34	21.13	7.16	2.39	0.11	3.38	0.37	1.57	2.29	3780
FA-C (%)	15.537	46.496	11.68	7.976	6.505	3.466	3.132	3.327	2.446	2.27	3060
GGBFS (%)	34.13	36.42	11.38	1.68	10.29	0.48	3.64	0.36	1.63	2.78	4190
LOI: Loss on ignition; SG: Specific gravity: BF: Blain fineness											

Types of Fiber Used to Reinforce the Geopolymer Concrete

Most of the fibers have a few millimeters of length. Therefore, their distribution in concrete is uncontrollable. They are usually orientated randomly in the concrete. So, it is suggested to be placed only at the required tension zone [38]. Steel, textile, organic, and glass fibers are the most common and widely used fibers in the past years [38]. The structural properties of fiber-reinforced concrete were studied using ductility, hardness, and post cracking strength [39]. In the lab, the results of various types of fibers were also observed [40]. The effect of aggregate and fiber reinforcement on concrete production costs was investigated [41]. They also addressed the impact of fiber orientation on structural characteristics.

Steel Fiber (Micro/Hooked) Steel Fiber. Steel fiber has functional properties. However, rust is the most critical consideration for steel fiber [42]. To overcome this defect, stainless steel can be utilized [42]. Table 3 presents the properties of steel fibers.

Table 3. Typical properties of Hooked and micro steel fibers.

Type of steel fiber	Length (mm)	Specific Gravity (g/cm^3)	Tensile strength (MPa)	Modulus of Elasticity (GPa)	Dimeter (mm)	Number per kilogram
Hooked	30	7.85	1.345	210	0.55	
Micro	13	-	2850	-	0.22	224862

Polypropylene Fiber. Alumina and silica are present in inorganic fibers. It has a high melting point, is chemically stable, has high tensile strength. The properties of polypropylene fiber are shown in Table 4.

Table 4. Typical properties of polypropylene fiber.

Length (mm)	Density (g/cm^3)	Tensile strength (MPa)	Modulus of Elasticity (GPa)	Water Absorbency	Alkaline and Acid Resistance	Melting Point
6	0.91	310	3.5	No	Excellent	160

Carbon Fiber. The carbon fiber has a 6–8 mm diameter, and its properties are summarized in Table 5.

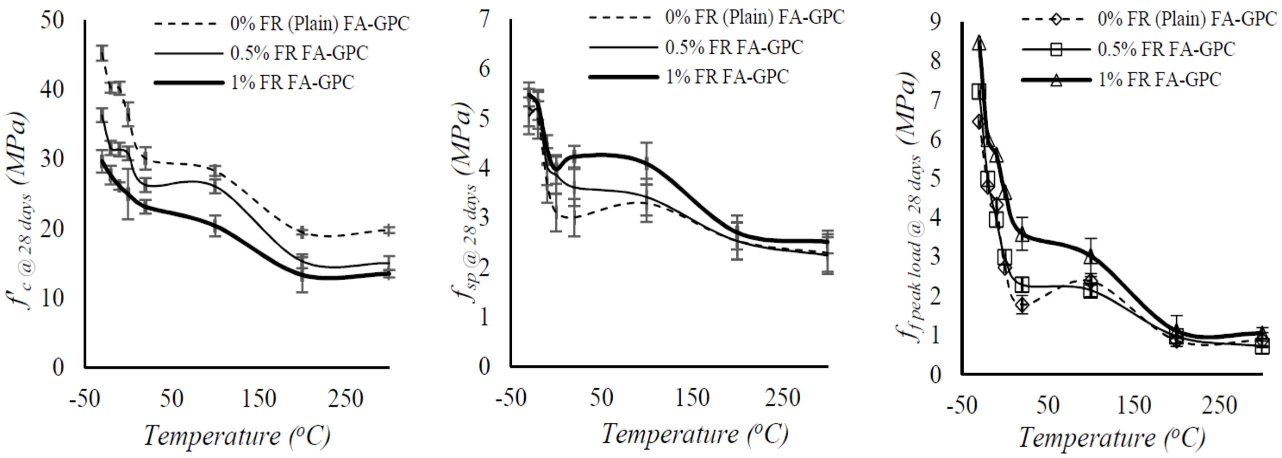
Table 5. Typical properties of carbon fiber.

Diameter (μm)	Density ($g\ cm^{-3}$)	Tensile strength (MPa)	Tensile modulus (GPa)
6–8	≥1.76	2930	200–220

Fire Resistance of Fiber Reinforced Geopolymers Concretes

The addition of fibers is an effective way to improve fracture toughness by reducing microcrack propagation when the material is subjected to load and controlling the sample's volumetric change during shrinkage [43] especially when the material is subjected to high temperatures. Researchers assess the mechanical properties of geopolymers reinforced with various fibers such as carbon [44], glass [45], polypropylene [46], and steel [47]. The reinforced samples confirmed higher flexural strength and modulus of elasticity and reduced autogenous and drying shrinkage, and improved volumetric stability at room temperature. Previous research also evaluated the thermal performance of the composites. In general, it was concluded that the addition of fiber at an appropriate ratio improves dimension stability in terms of minimizing thermal contraction, and it can withstand temperatures of up to 1000°C [46]. The mechanical properties of a one-dimensional carbon fiber reinforced geopolymer composite exposed to high temperatures were investigated. It was concluded that geopolymer composites' mechanical properties improved noticeably at elevated temperatures ranging from 1000 to 1300°C [44]. This could be due to increased carbon fiber and matrix interface bonding strength. However, the fibers decompose, allowing the mechanical properties to deteriorate when it exposed to the temperature over 1400°C [48]. Fiber reinforced geopolymers were investigated for fire resistance applications. It was determined that the addition of carbon fiber increased the mechanical properties of geopolymers at temperatures ranging from 200 to 500°C. Carbon fiber, on the other hand, had no discernible effect on compressive strength at 700°C [44].

In addition, it was investigated that the polypropylene fiber was the most suitable fiber among other varieties of fibers for thermal insulation applications and lightweight materials. This form can also be used in geopolymers that can withstand temperatures over 900°C [49]. Polypropylene fiber is inexpensive and highly resistant to environmental abrasion [50]. Steel microfiber (length 30mm and diameter 0.5mm) and polypropylene are distorted 4:1. (length 12 mm, 18 um diameter). It was indicated that the mechanical properties degraded with increasing temperature. The polypropylene and steel fiber reinforcement of fly ash type C geopolymers fiber dosage was 0, 0.5, and 1% by number. Researchers researched the fire resistance or behavior of geopolymers under elevated temperatures. Therefore, it is necessary to review the previously conducted studies to compare the research trends and evaluate the recent common achieved results. This study focused on the fire resistance of fiber-reinforced geopolymer composites. The role of fibers in mitigating the effects of fire on geopolymer composites was investigated. Figure 2 illustrates the mechanical properties of steel fiber reinforced geopolymer concretes [50].



(a) Compressive strength (f'_c). (b) Splitting Tensile Strength (f_{sp}). (c) Flexural Strength ($f_{t\ peak\ load}$).

Figure 2. Mechanical properties of fiber-reinforced GPC subjected to high temperatures [50].

Figure 3 reflects the influence of high temperatures on the cracking activity of steel fiber reinforced concrete (SFRC), steel fiber reinforced GPC (Sodium alkaline solution) SFRGC(Na), and steel fiber reinforced GPC (Potassium alkaline solution) SFRGC(K) [51]. Up to 400ºC, no cracks are visible in any of the concretes. However, at 600°C, the SFRC began to crack, and at 800°C, several large cracks on the surface appeared. The SFRGCs, on the other hand, escaped significant surface cracking at 800°C, though fine cracks appeared in a few places. It was discovered that after being exposed to different high temperatures, the color of the two forms of geopolymer concretes changed. The K-based geopolymer was significantly more reddish in color than its Na-based equivalent. The failure behavior of cylinders at ultimate compression load was studied in all three forms of concrete. At ultimate compression load, there was less disruption and spalling of concrete in SFRGC(Na) relative to its K-based equivalent and SFRC, the results being compatible with the compressive strength values. Concrete spalling in SFRGC(K) is very similar to SFRC at 600 and 800°C, which matches the findings [51].

Discussion

Geopolymers outperform ordinary Portland cement concrete in terms of fire resistance due to their interconnected pores, and water is not used in the geopolymerization method. High temperatures have a detrimental effect on the hydration cement paste due to water loss, while water is used in the hydration phase of OPC concrete [18]. The Si/Al ratio of the base material, for example, determines the fire resistance of geopolymer composites [23], the mixture's overall alkalinity [22]. The decline in the Si/Al ratio improved fire resistance, thus increasing the alkaline solution's molarity decreased strength loss after fire exposure. Fly ash-based geopolymer composites are more fire-resistant than metakaolin-based geopolymer composites because metakaolin needs more water to attain the necessary consistency. The higher the water level in the blend, the greater the porosity, resulting in increased pore pressure in the case of a fire that damages the composite [26].

Geopolymers are reinforced with a variety of fibers. The objective use of fibers is to strengthen the fire and mechanical properties of concrete. However, the researchers concluded that fibers only have a negligible effect on the fire resistance of concrete. Carbon fiber increased the fire resistance of composites up to 1300ºC. However, the material was weakened, and the fiber itself deteriorated after that 1300ºC [44]. Polypropylene fiber was evaluated to be the most suitable fiber for thermal insulation applications and lightweight materials compared to other fibers [53]. This form can also be used in geopolymers to resist temperatures of up to 900ºC [49]. Polypropylene fabric is inexpensive and highly resistant to environmental abrasion. Table 6 exhibited the results of some research studies previously conducted to examine the effect of volume fraction and types of fiber on the fire resistance of geopolymers composites. It is clear that regardless of the volume fraction and types of fiber, elevating temperature deteriorated the composites' mechanical properties. On the other hand, increasing the fiber content in the mixes led to decrease compressive strength. However, both splitting tensile strength and flexural strength increased.

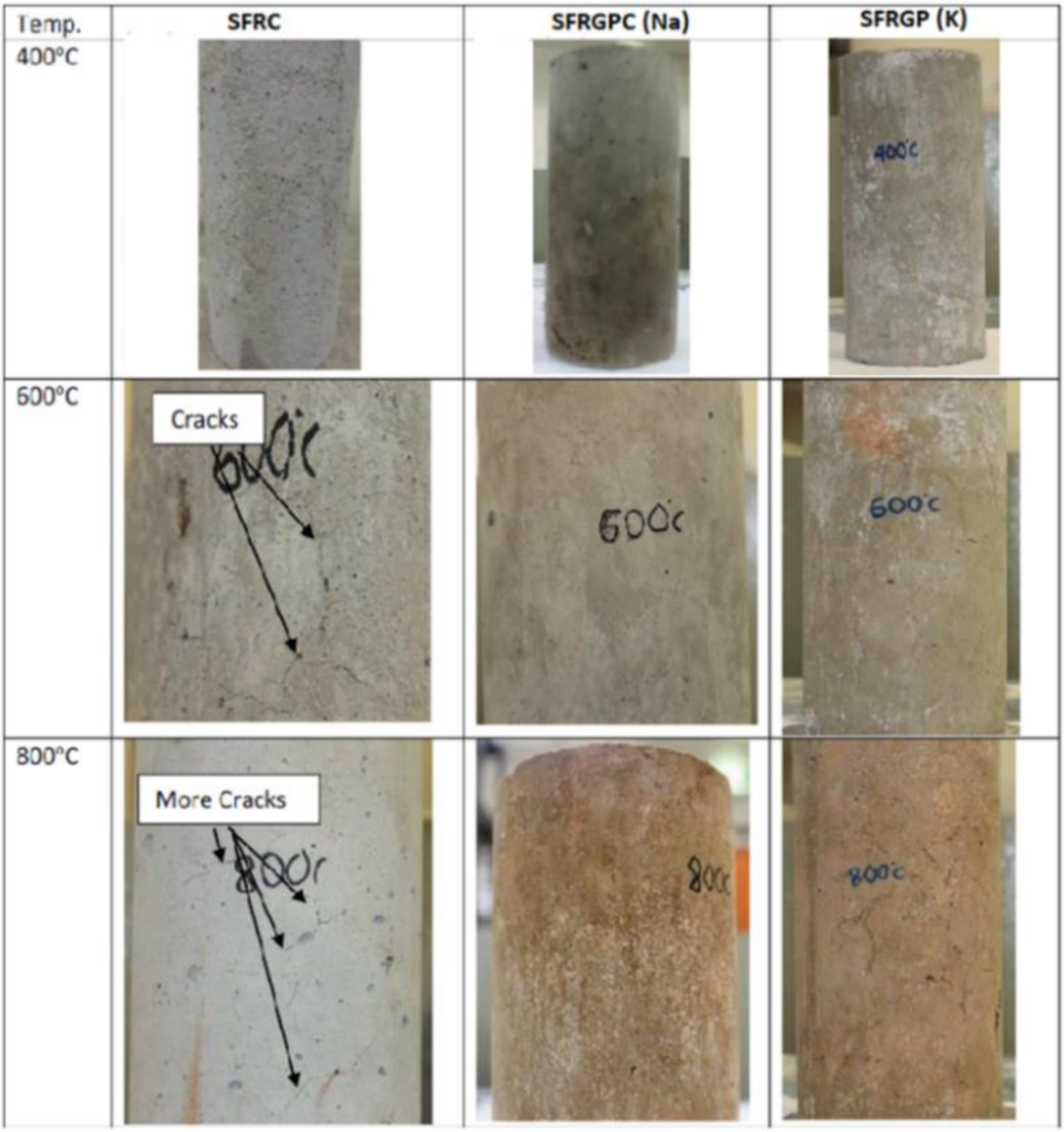


Figure 3. Surface cracking of SFRC, SFRGPC(Na) and SFRGPC(K) at 400, 600 and 800ºC [51].

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Table 6. The mechanical properties of fiber-reinforced GPC subjected to high temperatures.

References	**Fiber type**	**Fiber % (Volume)**	**Temperature (ºC)**						**Tests**
[44]	Carbon fiber		**Control**	**1000**	**1100**	**1200**	**1300**	**1400**	
		20	132.9	95.6	234.2	181.7	160.3	54.6	Flexure (MPa)
		20	3874.5	2354.8	4445.7	4233.4	2444.6	366.6	Fracture ($J\ m^{-2}$)
		20	36.5	30.4	63.8	55.9	50.6	41.5	E. Modulus (GPa)
[50]	Steel and polypropylene				**-30**	**100**	**200**	**300**	
		0.5			32	27	17	15	Compressive (MPa)
		1			28	21	13	11	
		0.5			3	3.5	2.3	2.2	S. Tensile (MPa)
		1			4	4.5	3	2.5	
		0.5			2.2	2	1.1	1	Flexure (MPa)
		1			3.5	2.5	1.3	1.2	
[49]	Polypropylene					**300**	**600**	**900**	
		0.8				46	29	11.5	Compressive (MPa)
		0.8				7.7	5.75	3	Flexure (MPa)

Conclusions

This analysis examines the factors that affect geopolymer concrete synthesis and their effect on binder characteristics. In addition, the parameters that influence the hardened properties of geopolymer concrete were extensively explored in light of the previous studies. A summary of the review is presented below: -

- The fire resistance of fiber-reinforced geopolymer concretes increased in the order of carbon fiber-based GPC, micro-steel fiber-based GPC, hooked steel fiber-based GPC, and polypropylene fiber-based GPC.
- Polypropylene fiber has lower melting properties. Therefore, it has no or limited influence on the fire resistance of geopolymer concrete.
- As compared to slag and metakaolin-based GPC, fly ash-based GPC has greater stability and fire resistance.
- Low calcium source materials primarily create N-A-S-H gel to bind aggregates, while high calcium precursors aid in forming A-S-H with Na in the binder structure. Therefore, high calcium fly ash exhibits fire resistance more than low calcium fly ash.
- Fly ash type C has superior fire resistance compared to fly ash type F.
- Geopolymers are a popular option for thermal resistance since they are more thermally resistant than OPC concretes.
- Geopolymers' superior fire resistance may be attributed to their interconnected pore formation. Also, no water is used in the production of geopolymerization. As a result, increasing the temperature does not affect the performance of geopolymerization.
- Water in the geopolymer pore absorbs heat, lowering the surrounding environment's temperature as the water evaporates and dries.
- The geopolymer concrete cured at ambient temperature has more fire resistance than the geopolymer concretes cured at the oven.
- Metakaolin-based geopolymers do not offer desired fire resistance due to the high water required to produce a workable mix. That leads to the porous structure of the production. Higher pore pressure causes the deterioration of metakaolin geopolymers.

- Fiber-reinforced GPC can be used as a sustainable and durable building material in a variety of construction applications where high performance is needed.

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