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The Behavior of Ceramic Fiber Geopolymer Concrete under the Effect of High Temperature

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Abstract: Geopolymer concrete (GC), also known as green concrete, contains slag, silica fume, and fly ash as binders. The absence of cement in concrete is critical to protect the world from the environmental impacts of cement production. In addition, exposure to high temperatures is a critical parameter that causes loss of strength in concrete. In this study, Geopolymer concrete samples were prepared with 10 different samples containing different proportions of slag, silica fume, and porous ash and subjected to various physical, mechanical, and optical tests. The sample (GS90) with optimum workability and compressive strength, which also showed high performance in water absorption, freeze-thaw, and UPV tests, was used in high-temperature tests. Portland cement concrete (PCC) was used as a control sample. This study investigated the effect of high temperatures on the physical and mechanical properties of fiber-free GCs containing 2%, 5%, and 10% by volume of ceramic fibers. Therefore, fiber-reinforced, fiber-free, and PCC specimens were subjected to high-temperature tests at 100, 300, 600, and 900 °C. As a result of the observation of crack growth, color changes, and compressive strength parameters in the samples subjected to high-temperature tests, the thermal resistance of the 10% ceramic fiber geopolymer concrete sample was 2.5% higher than other samples. There is no study in the literature that examines the behavior of ceramic fiber-reinforced geopolymer concrete at high temperatures. This research revealed an important finding by proving that ceramic fiber reinforcement increases the compressive strength of geopolymer concretes at a remarkable rate after high-temperature impact.

Keywords: geopolymer concrete; ceramic fiber; high temperature; slag; silica füme; fly ash

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1. Introduction

Fire, one of the environmental hazards, causes the deterioration of building materials. Color change and cracking occur in concrete structures due to high temperatures. At higher temperatures, serious decreases in the modulus of elasticity and compressive strength of concrete are observed [1].

Geopolymer concretes have higher thermal resistance compared to Portland Cement Concrete (PCC) due to their cement-free content [2,3]. In the event of a fire, it has been observed that reaching around 800 °C within the first half hour. Subsequently, it stabilizes at a constant temperature between 1000 °C and 1100 °C in approximately 2.0–2.5 h. Prolonged exposure to such high temperatures can result in severe damage and spalling of the concrete, which can disrupt the balance of the reinforcement and potentially lead to structural collapse. This situation can result in significant economic costs and poses a serious risk to human life [4,5]. It has been observed that high temperatures may lead to a decrease in compressive strength in PCCs. This is due to the increased thermal expansion of concrete, which can cause internal stresses, leading to concrete cracking and reduced strength. Additionally, high temperatures can cause structural transformation of minerals in concrete, which may also affect its strength. Moreover, it is worth noting that variations in thermal

expansion coefficients between the concrete and its aggregates could potentially result in the formation of cracks at the interfaces of the matrix phase.

According to studies in the literature, it has been observed that the compressive strength of geopolymer concrete cylinders and foamed porous, fly ash-based geopolymer paste specimens increases after exposure to high temperatures. Specifically, the compressive strength of geopolymer concrete cylinders was observed to increase after exposure to fire at 800 °C, while the compressive strength of foamed porous, fly ash-based geopolymer paste specimens increased after exposure to heat up to 1000 °C [6]. A study found that the compressive strength of geopolymer specimens increased at temperatures up to 200 °C. However, between temperatures of 200 °C and 1000 °C, the compressive strength decreased at different rates and in an unstable manner. Specifically, the compressive strength decreased steadily between temperatures of 600 °C and 800 °C and showed a sharp decrease between temperatures of 800 °C and 1000 °C [7].

The data presented in Table 1 indicates that the compressive strength loss of PCC is not significant up to 600 °C. However, it is worth noting that at temperatures above 600 °C, PCC has lost most of its compressive strength.

Table 1. High-temperature studies and compressive strength values in the literature.

References	Concrete Type	25 °C	100 °C	250 °C	300 °C	500 °C	600 °C	750 °C	900 °C	1000 °C
[3]	Geopolymer concrete	≅ 45	-	-	≅ 40	≅ 30	-	-	≅ 20	-
[3]	PCC with fly ash	≅ 22.5	-	-	≅ 17.5	≅ 12.5	-	-	≅ 5	-
[3]	PCC	≅ 32.5	-	-	≅ 22.5	≅ 17.5	-	-	≅ 5	-
[7]	Geopolymer concrete (SS/SH = 2.5 and cure temperature 25 °C)	≅ 35	≅ 50	≅ 55	≅ 54	≅ 50	≅ 45	≅ 30	≅ 20	≅ 15
[7]	Geopolymer concrete (SS/SH = 2.5 and cure temperature 80 °C)	≅ 40	≅ 65	≅ 68	≅ 65	≅ 60	≅ 50	≅ 35	≅ 23	≅ 20
[7]	Geopolymer concrete (SS/SH = 3.0 and cure temperature 25 °C)	≅ 45	≅ 55	≅ 65	≅ 63	≅ 55	≅ 50	≅ 35	≅ 20	≅ 15
[7]	Geopolymer concrete (SS/SH = 3.0 and cure temperature 80 °C)	≅ 75	≅ 85	≅ 88	≅ 85	≅ 80	≅ 77	≅ 55	≅ 20	≅ 15
[8]	PCC	39	≅ 39	-	≅ 35	-	≅ 20	-	≅ 10	-
[8]	PCC	76	≅ 76	-	≅ 76	-	≅ 45	-	≅ 15	-
[8]	PCC	120	≅ 120	-	≅ 120	-	≅ 60	-	≅ 20	-
[9]	PCC	57.6	-	53.3	-	46.1	-	30.8	-	8.5
[9]	PCC with silica fume	62.6	-	55.2	-	47.6	-	32.3	-	6.2
[9]	PCC with carbon fiber	54.3	-	46.2	-	40.5	-	35.3	-	7.3
[9]	PCC with silica fume and carbon fiber	60.2	-	48.1	-	40.8	-	28.6	-	4.1
[10]	PCC	≅ 50	-	≅ 45	-	≅ 40	-	≅ 25	-	-

Table 1. *Cont.*

References	Concrete Type	25 °C	100 °C	250 °C	300 °C	500 °C	600 °C	750 °C	900 °C	1000 °C
[10]	PCC with fly ash	≅ 40	-	≅ 38	-	≅ 37	-	≅ 15	-	-
[11]	PCC	≅ 79	-	-	≅ 75	≅ 45	-	-	-	-
[11]	PCC with steel fiber	≅ 93	-	-	≅ 85	≅ 55	-	-	-	-

SS: Sodium silicate SH: Sodium hydroxide.

Lau et al. conducted a study on the effect of using steel fibers in high-temperature concrete and found that it resulted in improved mechanical properties and higher thermal resistance [12]. In the study conducted by Wang et al., the impact of high temperatures on concrete with added glass fibers was examined. The results indicated that the flexural strength of the concrete decreased with the addition of short glass fibers in high amounts, while the flexural strength increased with the addition of long glass fibers in high amounts. Furthermore, the compressive strength of the concrete decreased when long glass fibers were utilized at high temperatures [13]. In their study, Bezerra et al. found that steel fiber-reinforced concrete demonstrated superior mechanical behavior at high temperatures compared to concrete without fiber reinforcement. It is worth noting that the addition of steel fiber did not have any significant effect on the compressive strength of the concrete [14]. A study was conducted by Abaeian et al. on the impact of high temperatures on concrete with added polypropylene fiber. The study found that the addition of polypropylene fiber had a slightly positive effect on reducing the negative impact of high temperatures on concrete, including losses in tensile, flexural, and compressive strength [15]. Duan et al. compared the performance of cement-stabilized macadam using static and vibratory compression methods in their study. In the vibratory compression method, less crack formation and samples that are more resistant to temperature cycles were obtained compared to static compression [16]. It is worth noting that in high-temperature studies of fiber-reinforced concrete, the addition of fibers is typically used to enhance flexural and tensile strength. In this study, ceramic fiber was added to the dry mix by dissolving it in activators and water, which allowed for the homogeneous distribution of the ceramic fiber throughout the concrete's internal structure. The ceramic fiber was evenly distributed throughout the internal structure of the concrete, acting as a protective cover and mitigating the effects of high temperatures. The objective of this study is to mitigate the decrease in compressive strength of concrete under high-temperature conditions while simultaneously preserving its flexural and tensile strength.

Geopolymeric concrete requires different binders than PCC. These binders are alkaline fluids and pozzolanic materials. Pozzolanic materials consist of materials such as metakaolin, fly ash, and slag, which are rich in silica (Si) and aluminum (Al) [17,18]. The polymerization of aluminosilicates of pozzolanic materials forms geopolymer concrete. These aluminosilicates significantly affect geopolymer concrete's physical and mechanical properties [19,20]. The pozzolanic materials used in this study are slag, silica fume, and fly ash. Silica fume increases the strength of cementitious and geopolymeric matrices by reducing the void ratio [21]. Aygörmez et al. found that using silica fume in their studies reduced the gap rates of geopolymeric matrices and thus increased the bending strength with pressure strength. However, excessive silica fume negatively affected pressure resistance and bending strength [5]. Slag occurs as a by-product of iron and steel production [22]. In their study, Saladung, Ogawa, and Kawai investigated the effect of blast furnace slag addition on the mechanical properties of fly ash-based geopolymers. As a result of this study, it was determined that the addition of blast furnace slag significantly increased the compressive strength due to the formation of calcium silicate hydrate (C-S-H) gel, which helps create a denser structure [23]. Another study revealed that adding blast furnace slag

to fly ash-based geopolymers could improve setting time [24]. In their study, Al-Rawi and Tayşi examined the effects of steel fiber and blast furnace slag content on the fresh and hardened properties of self-compacting fly ash-based geopolymer concrete. Blast furnace slag was reinforced into geopolymer concrete at 0%, 25%, 50%, 75%, and 100% by weight. They found that the increase in the proportion of blast furnace slag had a negative effect on the properties of fresh concrete, but it significantly increased the compressive strength [25]. Keerthy and Kumar tried to achieve the best compressive strength in their study by using different proportions of blast furnace slag and fly ash. The results show that reducing the proportion of blast furnace slag and substituting fly ash causes a decrease in compressive strength [26]. Fly ash is a pozzolanic material formed by coal combustion and is widely found in nature [27,28]. Palomo, Grutzeck, and Blanco found that different fly ash specimens cured at 85 °C for 24 h had compressive strengths between 35 and 40 MPa. However, by adding glass water to the NaOH activator in fly ash-based geopolymer concrete, the compressive strength reached approximately 90 MPa [29]. The alkaline liquids used in this study are sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). In their study, Yasaswini and his colleagues found that the high-temperature resistance of geopolymer concrete increased as the amount of sodium silicate increased [30].

Several studies have been conducted on the behavior of PCC, and geopolymer concretes under high temperatures. However, there is a noticeable gap in research on the high-temperature behavior of ceramic fiber-added concrete. The objective of this study is to improve the mechanical performance of concrete against high temperatures by incorporating ceramic fibers, which dissolve upon contact with liquid, into the concrete. This study explores the behavior of ceramic fiber and geopolymer concrete under high temperatures and presents noteworthy findings to the literature.

2. Material and Method

The flow chart of the study is given in Figure 1. Various experiments, such as compressive strength, UPV, and SEM, were carried out on different types of specimens. In this way, the specimen content to be used in high-temperature tests was determined. With this content, those with different fiber ratios were prepared and subjected to high-temperature testing.

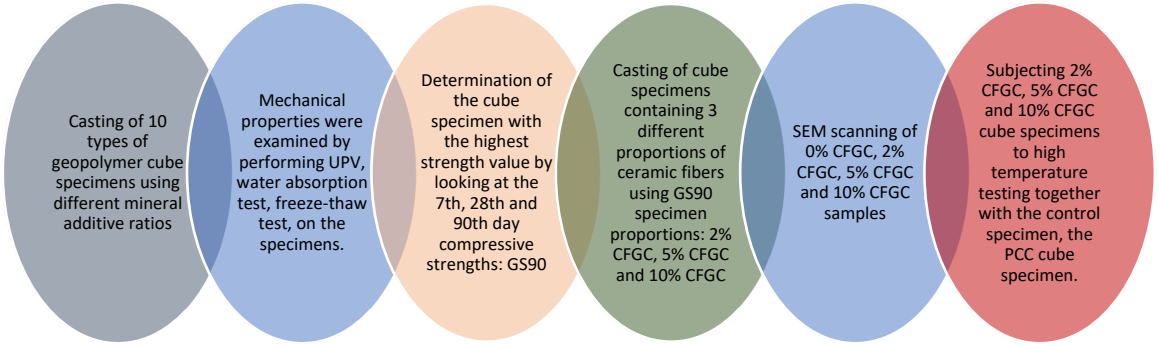


Figure 1. Flow chart of the study.

This article aims to explore the development of geopolymer concrete with enhanced high-temperature resistance. To achieve this, ceramic fiber, known for its temperature resistance, has been added to the mixture. The primary test conducted was the high-temperature test. Other experiments were performed to determine the optimal mixing ratio for geopolymer concrete, resulting in the identification of the ratio that yields the highest mechanical properties. The homogeneity of ceramic fiber distribution in geopolymer concrete was assessed through SEM analysis.

The purpose of this procedure is to investigate the high-temperature behavior of ceramic fiber concretes and to obtain concrete that does not lose its strength against high temperatures. For this purpose, ceramic fiber that can dissolve and disperse homogeneously

in liquid was used, and its high-temperature behavior was investigated. This research is a study that has no examples in the literature and provides positive data.

2.1. Material

Within the scope of this study, slag (Oyak Çimento, Mersin, Turkiye), silica füme (ETİ elektrometakurji A.Ş., Antalya, Turkiye), fly ash (Cenal Elektrik A.Ş. Çanakkale, Turkiye), ceramic fiber (RBS Ravago A.Ş., Kayseri, Turkiye), superplasticizer (Polisan, İzmir, Turkiye), Na_2SiO_3-NaOH (EMA Grup A.Ş, İzmir, Turkey), fine aggregate and coarse aggregate (Dersim Beton Ltd.Şti.,Tunceli, Tukiye) were used when manufacturing geopolymer concrete. The chemical analysis results of ground slag, fly ash, and silica fume are given in Table 2.

Table 2. Chemical analysis results of ground slag, fly ash, and silica füme (% by weight).

Oxides	Slag	Fly Ash	Silica Fume
SiO_2	39.14	59.37	70–80
Al_2O_3	13.30	21.40	2.55–4.10
Fe_2O_3	1.50	8.62	1.17–5.00
CaO	33.00	3.24	1.06–1.80

The chemical composition and particle sizes of slag, fly ash, and silica fume are given by the manufacturer. Slag and fly ash have particle sizes below 100 µm, while silica fume has particle sizes below 25 µm.

The chemical analysis results of alkaline liquids NaOH and Na_2SiO_3 are in Tables 3 and 4.

Table 3. Chemical analysis of NaOH (% by weight).

Na_2CO_3 (≤)	Na_2SO_4 (≤)	$NaClO_3$ (≤)	Cl (≤)	SO_4 (≤)	Fe (≤)
0.5	0.008	0.008	0.005	0.005	0.001

Table 4. Chemical analysis of Na_2SiO_3.

Na_2O (% by Weight)	SiO_2 (% by Weight)	Fe (ppm)
13.5–15	27–30	100 Max.

Ceramic fiber is a material with high thermal resistance. For this reason, it is used in molten form in metal casting sprues. In this way, the thermal resistance of the sprues increases and can withstand high temperatures. This study aims to explore the potential of utilizing ceramic fiber, a material known for its high thermal resistance and commonly used in metal casting runners, to enhance the thermal resistance of geopolymer concretes. The objective is to investigate the feasibility of this method in enabling geopolymer concretes to withstand high temperatures. Ceramic fiber, which increases the thermal resistance in casting runners, is expected to have a similar effect in geopolymer concrete. The results of ceramic fiber's physical and chemical analysis are given in Tables 5 and 6.

This study examined the dissolution performance of ceramic fiber in various liquids, namely NaOH, Na_2SiO_3, water, and superplasticizer, over 24 h in a laboratory environment. The results indicated that the ceramic fiber dispersed uniformly in superplasticizer and NaOH, demonstrating superior dissolution performance compared to water and Na_2SiO_3. During the casting of geopolymer concrete, the fiber was dissolved with the aid of activators and water before being added to the solid mix. It has been determined through SEM and EDS scans that the ceramic fiber was evenly distributed throughout the internal structure of the geopolymer concrete. Figures 2–5 show the dissolution state of the ceramic fiber after being kept in different liquids for 24 h.

Table 5. Physical analysis of ceramic fiber.

Physical Properties	Unit	Specification
Fiber Average Diameter	μm	2.6–3.4
Fiber Length	mm	Max. 250
Continuous Use Temperature	°C	1050–1093
Fire Reaction Class	-	A1
Classification Temperature	°C	1260
Melting Point	°C	1760
Specific Temperature 1090 °C	kJ/kg	1.3

Table 6. Chemical analysis of ceramic fiber.

Chemical Properties	Na_2O	Al_2O_3	SiO_2	ZrO_2	CaO
Specification (% By Weight)	1.38	44	52	0.25	0.60

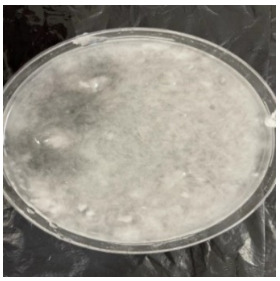


Figure 2. The ceramic fiber soluble in superplasticizer.

Figure 3. The water-soluble ceramic fiber.

Figure 4. The ceramic fiber soluble in Na_2SiO_3.

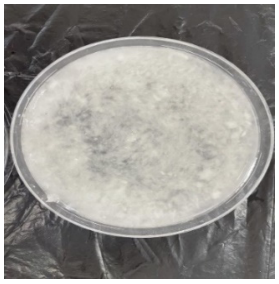


Figure 5. The ceramic fiber soluble in NaOH.

The suitability of the aggregates for producing geopolymer concretes was assessed through specific gravity, water absorption, and sieve analysis tests. The sieve analysis test results are given in Figure 6.

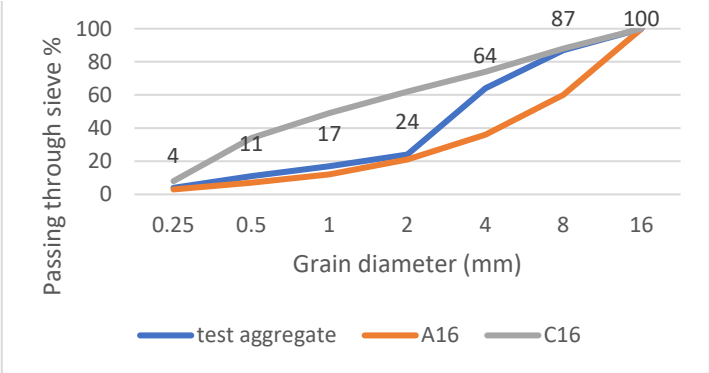


Figure 6. Aggregate granulometry curve.

The graph above displays the granulometry curve resulting from the sieve analysis experiment. The tested aggregate fell within the limit values of A16 and C16, which are the reference curves. Table 7 presents the results of the water absorption and specific gravity tests of the aggregates.

Table 7. Water absorption and specific gravity results.

	Symbol	Coarse Aggregate	Fine Aggregate
Dry specific gravity (gr/cm^3)	δ_k	1.61	2.02
Saturated-surface dry weight (gr/cm^3)	δ_{ydk}	1.64	2.37
Apparent specific gravity (gr/cm^3)	δ_g	1.66	2.65
Water absorption capacity (%)	S_a	1.72	2.4

2.2. Method

This study involved preparing ceramic fiber geopolymer concrete (CFGC) specimens with varying quantities of slag, silica fume, and fly ash, as well as a control specimen with PCC. These preliminary study specimens underwent testing through UPV, water absorption, freeze-thaw, compressive strength, SEM, and EDS scanning, as well as high-temperature tests. The geopolymer concrete specimen with the highest compressive strength and lowest void ratio (GS90) was chosen for high-temperature testing. Subsequently, ceramic fiber was added to the concrete at varying volumes of 2%, 5%, and 10%, and high-temperature tests were conducted at 100, 300, 600, and 900 °C. The geopolymer concretes have been named 0% CFGC, 2% CFGC, 5% CFGC, and 10% CFGC, based on the amount of ceramic fiber they contain. The mixing ratios for the geopolymer concrete are displayed in Table 8.

Table 8. Geopolymer concrete mixing ratios (kg/m^3).

Specimen Name	Fine Aggregate	Coarse Aggregate	Binders			Activators		Super Plasticizer
			Silica Fume	Slag	Fly Ash	Na_2SiO_3	NaOH	
G100	1209	651	0	400	0	115	46	4
GF90	1209	651	0	360	40	115	46	4
GF80	1209	651	0	320	80	115	46	4
GF70	1209	651	0	280	120	115	46	4
GS90	1209	651	40	360	0	115	46	4
GS80	1209	651	80	320	0	115	46	4
GS70	1209	651	120	280	0	115	46	4
GS50	1209	651	200	200	0	115	46	4
S100	1209	651	400	0	0	115	46	4
GSF50	1209	651	200	100	100	115	46	4

For more details on the tests performed, see Table 9.

Table 9. Tests and standards to be applied to geopolymer concrete specimens.

Experiment	Standard	Number of Specimens	Specimen Sizes
Sieve Analysis Test	TS EN 933-1.2012	The aggregates	Non-destructive testing
UPV	TS EN 12504-4	10 sets	Non-destructive testing
Determination of water absorption amount	TS EN 12350-6	10 sets	Non-destructive testing
Compressive Strength Test	TS EN 12390-3	30 sets	10 × 10 × 10 cm
Freeze-Thaw Test	TSE CEN/TR 15177	10 sets	10 × 10 × 10 cm

1 set consists of 3 specimens of the same content.

Initially,the flow diameters of each casting specimen were also examined to determine the workability of the concrete. According to Figure 7, it can be observed that the G100 specimen, which had 100% slag content, exhibited the lowest workability. As the slag ratio increased in the specimens, the fluidity of the concrete mix decreased [31]. Additionally, the setting time of the concrete was shortened with an increase in slag content [32], leading to a low spreading diameter for the G100 specimen with 100% slag content. Moreover, it was observed that the S100 specimen contained fine-grained silica fume, which absorbed the liquid in the mixture, leading to a decrease in workability. In contrast, the GSF50 specimen demonstrated the most favorable workability. Additionally, the workability of the GF90 specimen, where the slag rate was reduced to 90% and 10% fly ash was used as a substitute, showed an increase of 8.43% when compared to the G100 specimen. The workability of the GS90 specimen, which contains 90% slag and 10% silica fume, increased by 24.10% compared to G100, and this specimen also performed better in high temperature tests.

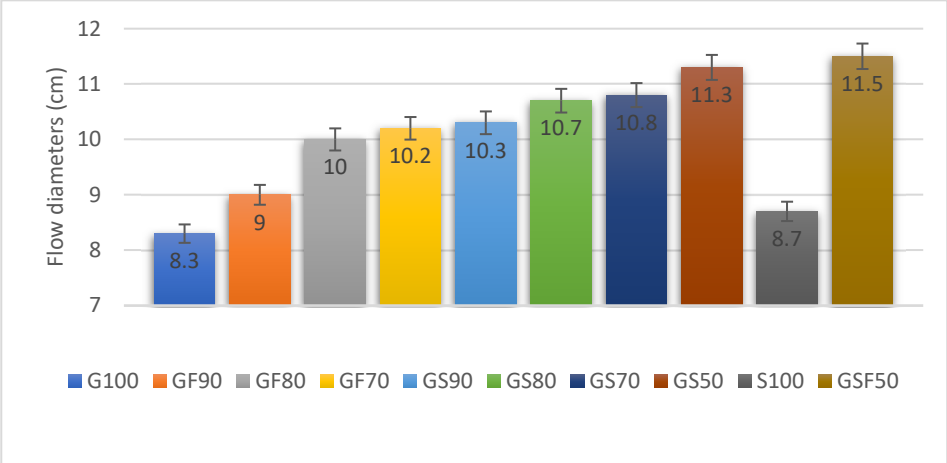


Figure 7. The flow diameters of pre-test specimens.

In this part of the research, specimens were prepared with the composition of the GS90 specimen with the highest machinability and compressive strength, with different ceramic fiber ratios, and exposed to high temperatures. The loss of compressive strength and other visual changes due to high temperatures were carefully observed.

In the high-temperature test, losses of compressive strength and color changes of 0% CFGC, 2% CFGC, 5% CFGC, and 10% CFGC cube specimens were examined after 100 °C, 300, 600, and 900 °C exposure. PCC was used as a control specimen in high-temperature tests. Within the scope of this study, ceramic fiber geopolymer concrete (CFGC) specimens and control specimen PCC were tested.

PCC was produced using CEM II 52.5 cement. In order to achieve the desired consistency, a plasticizing chemical additive was added to the mixture at a rate of 1% of the binder, which is consistent with other specimens. The Fine/Course aggregate ratio is 0.55, and the aggregates used were crushed stream aggregate from the same mixture as GFGC. The PCC concretes were left in the mold for 24 h and then cured in the curing pool until the 28th day.

3. Results and Discussion

This study aimed to determine the optimal mixture content for geopolymer concrete exposed to high-temperature tests on fibrous specimens. Non-fibrous geopolymer specimens were prepared in varying proportions and subjected to water absorption, compressive strength, freeze-thaw, UPV, and high-temperature tests. The results were analyzed to determine the most suitable mixture content for the geopolymer concrete.

Upon examining the water absorption graph in Figure 8, it appears that the GSF50 specimen absorbed less water than the other specimens. It is worth noting that the specimens with low workability, namely G100 and S100, absorbed the most water. The remaining eight specimens, which contained different mineral additives, exhibited similar water absorption values due to their higher workability compared to G100 and S100. It was observed that as the workability of concrete increases, there is a corresponding decrease in the water absorption rate, which can be attributed to the reduction in voids.

In order to ensure the compressive strength of geopolymer concrete specimens, 30 sets were prepared without the addition of ceramic fibers. The compressive strength was measured on the 7th, 28th, and 90th day. These results are presented in Figure 9.

Previous studies in the literature have shown that reducing the amount of slag in geopolymer concrete and replacing it with fly ash results in a decrease in compressive strength [33]. In this study, the compressive strength at 7, 28, and 90 days is reduced by reducing the slag and replacing it with fly ash, similar to other studies in the literature [26,33–35].

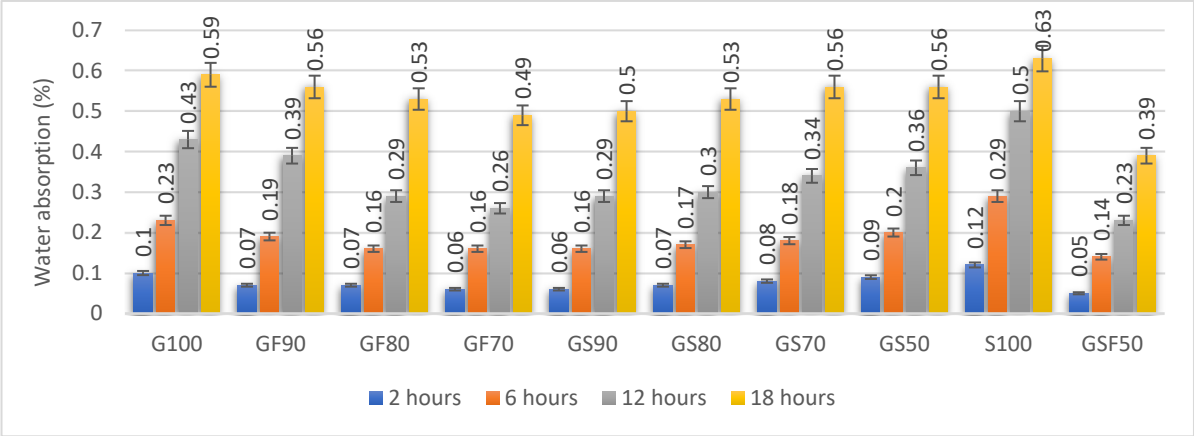


Figure 8. Water absorption percentages of geopolymer concrete specimens.

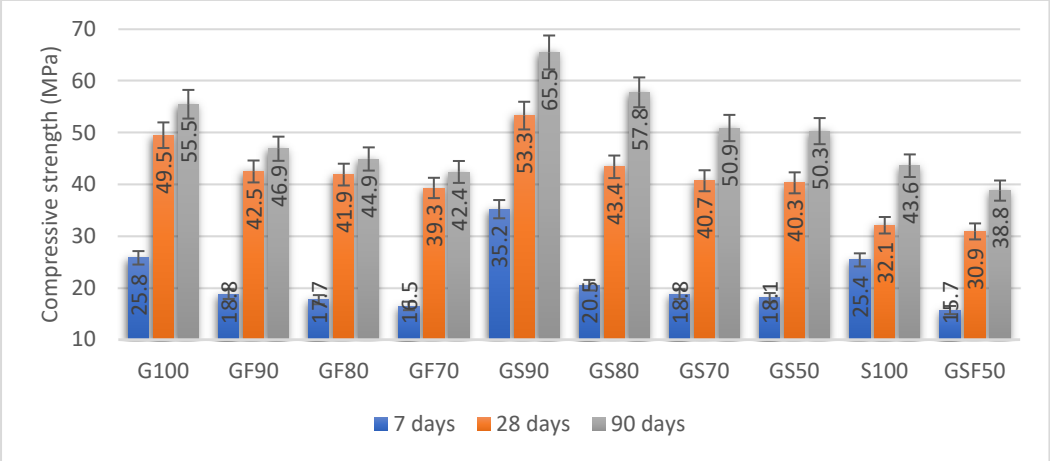


Figure 9. Compressive strength graph of geopolymer specimens on the 7th, 28th, and 90th days.

By reducing the slag content by 10% and adding silica fume instead, the compressive strength increased by 10–20% compared to the 100% slag specimen, and the compressive strength of the 20% silica-added specimen was similar to that of the G100 specimen. Adding a certain amount of silica fume to concrete positively affected the compressive strength [21,36]. On the other hand, adding more than 10% silica fume to concrete negatively affected the compressive strength [5].

The GS90 specimen had the highest compressive strength values among the other specimens on the 7th, 28th, and 90th day. The specimen that reached 65 MPa compressive strength on the 90th day was also the most suitable for workability. The compressive strength of the slag-only specimen was about 30% lower than the GS90 specimen. The 10% silica additive in the GS90 specimen improved the physical and mechanical properties of the slag-based mortar, which agrees with other studies in the literature [21,36]. The test results indicate that increasing the slag rate increases the compressive strength. However, using only slag reduces the compressive strength as the void structure in the material increases due to the decrease in workability. Therefore, it is recommended to add 10% silica fume to improve workability and reduce void structure, increasing compressive strength. When silica fume is added in quantities greater than 10%, the CaO ratio decreases, which in turn leads to a decrease in compressive strength as the slag ratio decreases. It is worth noting that the GS90 specimen exhibits the highest compressive strength value.

The UPV test was performed on the 28th day to predict the void structure within the cast pre-test specimens. The results of the UPV test are shown in Figure 10.

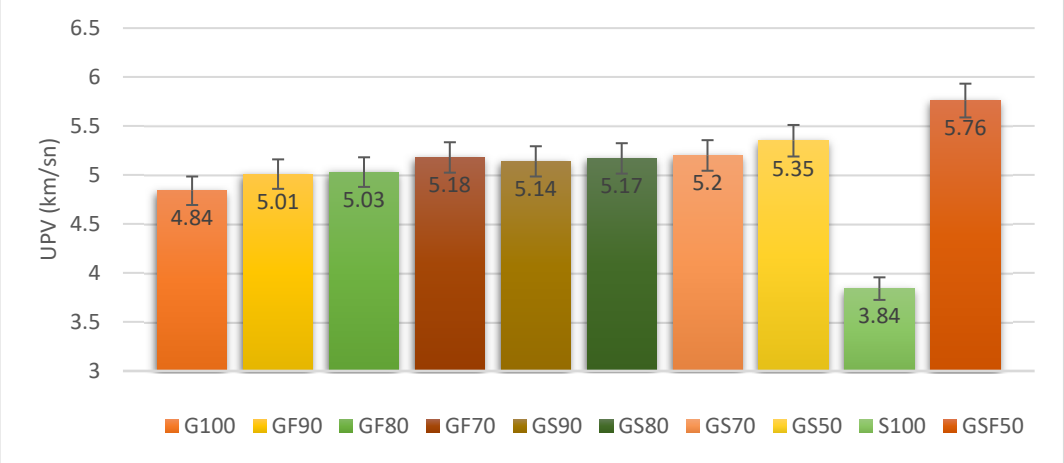


Figure 10. 28th-day UPV test (km/sec) on pre-test specimens.

When the UPV test was performed on the specimens that had been waited for 28 days, it was determined that the substitution of silica fume and fly ash reduced the voids in the specimens. However, it was observed that the compressive strength value decreases when the substitution of silica fume in geopolymer concrete is more than 10% [5]. Also, the void ratio in geopolymer concrete specimens decreased as the fly ash replacement increased. However, although the void ratio decreased, the compressive strength value decreased [33]. This is because as the rate of slag, which is the main binder, decreases, the rate of CaO reaction in the geopolymer concrete also decreases. As the CaO ratio in the specimens decreases, the geopolymerization rate is reduced [35].

The aim of this study is to develop concrete that can withstand high temperatures while also being able to endure the regions and adverse climatic conditions in which it will be used. In order to assess the concrete's suitability for cold weather conditions, a freeze-thaw test was carried out. It is worth noting that the mechanical strength of concrete tends to decrease as the void ratio in its internal structure increases, which can be caused by exposure to the freeze-thaw cycle. Additionally, this may result in a reduction in the concrete's high-temperature resistance.

As shown in Figure 11, the results of the freeze-thaw test indicate that all specimens, except for G100 and S100, experienced a similar percentage of weight loss. The compressive strength, ultrasonic pulse velocity (UPV), and water absorption tests suggest that the G100 and S100 specimens have high void structures, as evidenced by their high freeze-thaw weight loss and low workability.

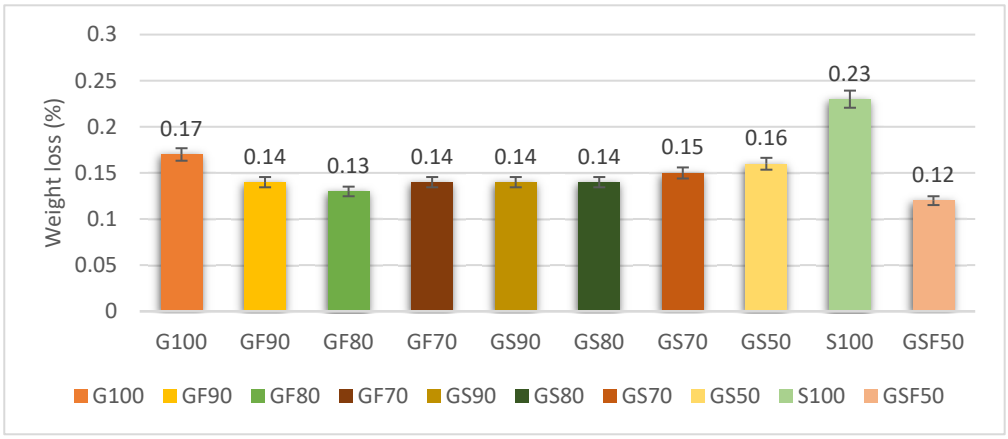


Figure 11. Weight loss as a result of freeze–thaw test (%).

This study employed scanning electron microscopy (SEM) to detect the micro-internal structure of CFGC.

SEM and EDS scans were performed on specimens containing 2%, 5%, and 10% CFGC. Figure 12 displays the SEM scan of the ceramic fiber, while Figure 13 illustrates the percentage distribution of atoms in the ceramic fiber due to EDS analysis.

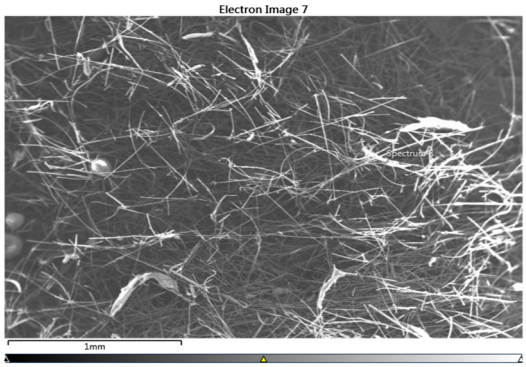


Figure 12. EDS scan of ceramic fiber.

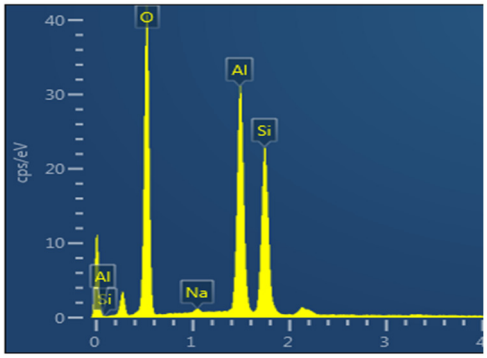


Figure 13. Atomic distribution of ceramic fiber.

Upon examining the data in Figure 13, it can be observed that the ceramic fiber is primarily composed of oxygen (O), aluminum (Al), and silicium (Si). Through the examination of this data, it is possible to compare the atomic ratios in GS90 specimens that were cast with varying ceramic fiber ratios. SEM images and EDS scans of CFGC specimens are displayed in Figures 14–19. The ceramic fibers are marked with yellow rings in the SEM images.

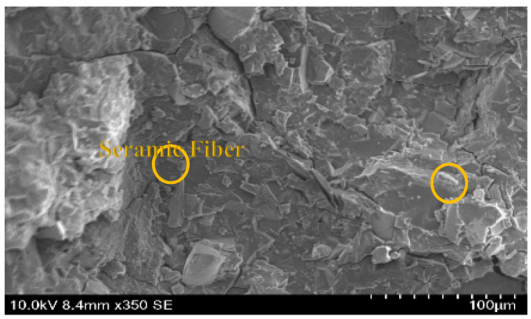


Figure 14. SEM image of 2% CFGC.

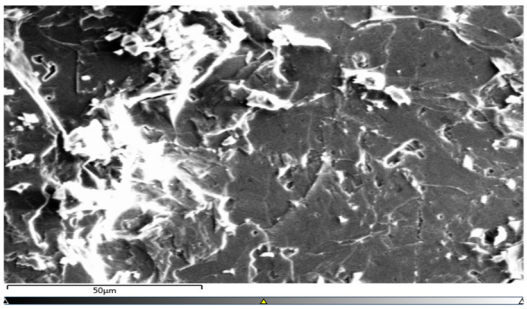


Figure 15. EDS image of 2% CFGC.

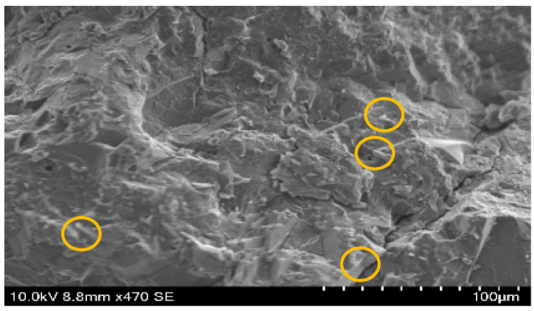


Figure 16. SEM image of 5% CFGC.

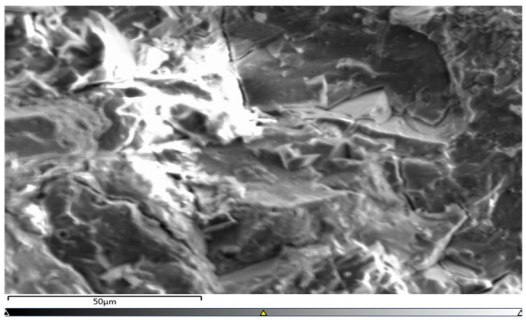


Figure 17. EDS image of 5% CFGC.

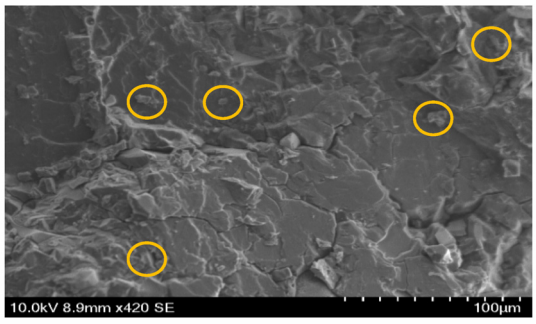


Figure 18. SEM image of 10% CFGC.

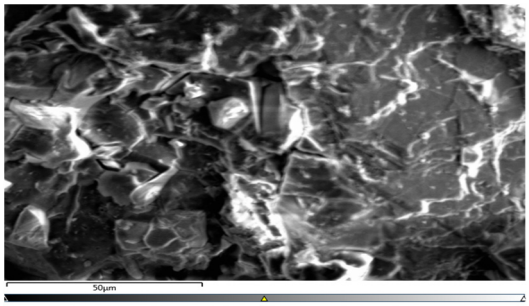


Figure 19. EDS image of 10% CFGC.

Table 10 gives the atomic distributions of 2%, 5%, and 10% CFGC specimens.

Table 10. Atomic distribution of 2%, 5%, and 10% CFGC specimens (% by weight).

	2% CFGC	5% CFGC	10% CFGC
Element	**Atom (%)**	**Atom (%)**	**Atom (%)**
C	21.45	15.26	17.14
O	59.83	58.07	61.65
Na	0.69	2.00	3.19
Ca	15.72	16.00	9.22
Mg	0.57	1.18	1.20
Si	1.36	5.97	5.98
Al	0.34	1.52	1.48

Upon examination of the SEM images, it was observed that the ceramic fiber had dissolved and was evenly distributed throughout the geopolymer concrete. Specifically, the substitution of ceramic fiber in the GS90 geopolymer specimen resulted in an increased ratio of Si and Al. This can be attributed to the fact that the primary components of the ceramic fiber are composed of Si and Al. It has been observed that the fire resistance of geopolymer concrete can be improved by increasing the ratio of Si elements.

Furthermore, it is possible to incorporate ceramic fiber into geopolymer concrete as a high-temperature resistant material. The objective of this study is to examine the effects of high temperatures on concrete and propose the addition of ceramic fiber to geopolymer concrete.

A review of studies measuring the high-temperature behavior of concrete reveals that compressive strength is typically measured after specimens are exposed to a high-temperature oven for two hours and then returned to room temperature. In this study, the concrete specimens were cooled to room temperature by preventing moisture absorption. The oven was preheated to the desired temperature before the specimens were placed inside for testing. Following a 2-hour wait at the specified temperature, the samples were removed from the oven. The compressive strength tests were conducted at room temperature in accordance with the standards. The specimens were kept in a moisture-free environment and allowed to cool for approximately 30 minutes before being subjected to compressive strength tests. The concretes were cooled either in air to prevent changes in internal stress due to temperature from affecting the compressive strength. Figure 20 displays the compressive strength of the specimens after the high-temperature test..

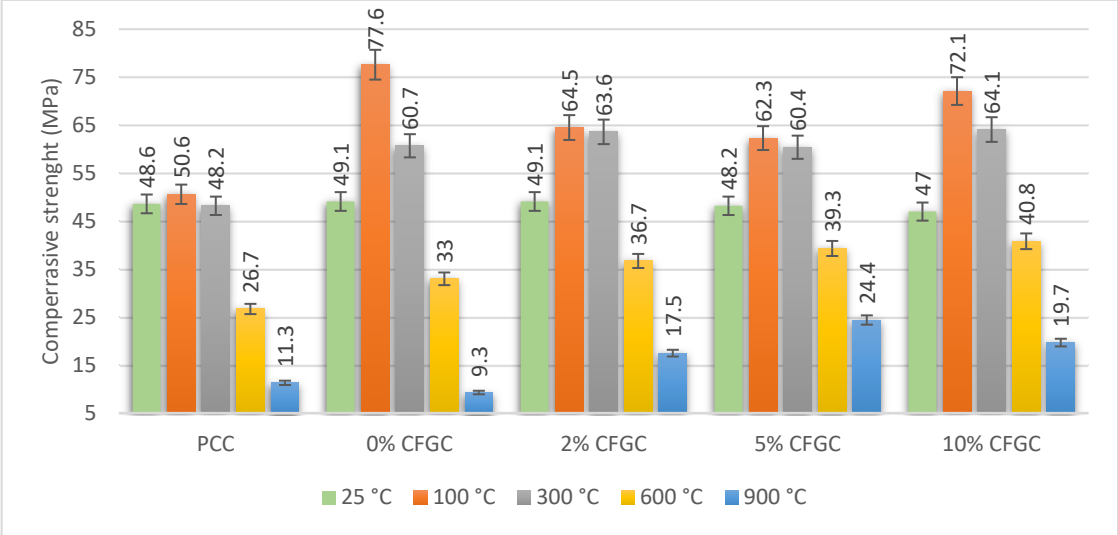


Figure 20. Compressive strength of geopolymer concrete after high-temperature test (MPa).

According to Figure 20, it can be observed that all the concretes in the study maintained their compressive strength up to 100 °C. Additionally, the geopolymer concrete specimens experienced a thermal cure, resulting in strength increases of 29–59%. On the other hand, PCC specimens only showed a slight increase of approximately 4% up to 100 °C, after which they began to lose strength. Although the geopolymer specimens experienced a reduction in strength, they remained stronger than both their room temperature strength and the strength of the PCC specimen up to 600 °C. As per the literature, it has been reported that geopolymer concretes can maintain their compressive strength up to 600 °C [37].

The compressive strength of the fiber-reinforced geopolymer concrete specimens remained largely intact up to 300 °C, in contrast to the PCC specimens. At 900 °C, the maximum compressive strength of the PCC and fiberless geopolymer specimens was 11.3 and 9.3 MPa, respectively. However, the compressive strength of the 5% and 10% fiber specimens remained intact up to 24.4 and 19.7 MPa, respectively. Considering that all other parameters are the same, it could be concluded that this difference is due to the presence of ceramic fiber.

Figures 21–24 show images of the specimens before and after the high-temperature test at 600 and 900 °C.

The specimens tested at the high temperature of 600 °C experienced a compressive strength decrease of 45.06% for PCC, 32.79% for 0% CFGC, 25.25% for 2% CFGC, 18.46% for 5% CFGC, and 13.19% for 10% CFGC compared to their room temperature strength.

At 900 °C, the specimens lost compressive strength at a rate of 76.75% for PCC, 81.06% for 0% CFGC, 64.36% for 2% CFGC, 49.38% for 5% CFGC, and 58.09% for 10% CFGC, compared to their room temperature compressive strength.

Figure 21. View of the PCC and 5% fiber sample before testing at 600 °C.

Figure 22. View of the PCC and 5% fiber sample after testing at 600 °C.

Figure 23. View of the PCC and 10% fiber sample before testing at 900 °C.

Figure 24. View of the PCC and 10% fiber sample after testing at 900 °C.

Table 11 depicts the before and after test states of 2%, 5%, and 10% CFGC specimens, geopolymer concrete without fiber addition, and PCC at 900 °C.

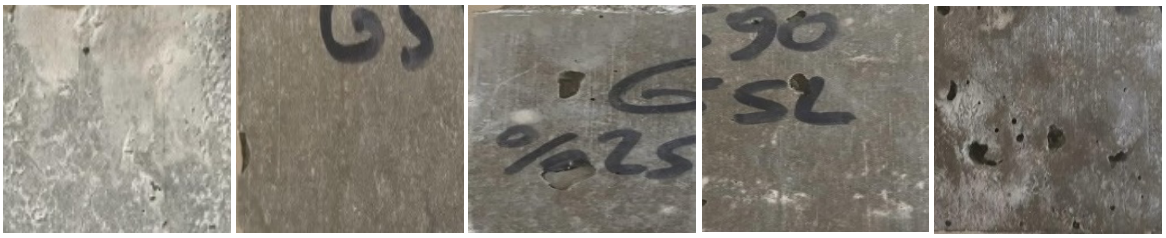
Upon examination of the specimens exposed to 600 °C and 900 °C temperatures, it was observed that most of the cracking damage occurred in PCC. However, the cracking damage in 5% CFGC and 10% CFGC specimens is comparatively less than in the other specimens. Additionally, previous studies have shown that as the compressive strength loss in the specimens increases, the cracking damage also increases. During the tests, it was observed that the use of ceramic fiber in geopolymer concrete reduced cracking and resulted in a decrease in strength.

As shown in Figure 25, the specimens subjected to the high-temperature test at 600 °C displayed a general view, while Figure 26 shows the specimens at 900 °C.

Figures 25 and 26 show 2%, 5%, 10% CFGC, 0% CFGC and PCC specimens, from left to right respectively. When the color scales of the geopolymer concrete specimens were examined after high temperature, it was observed that the concrete surface color changed from light to dark shades as the strength loss increased [38]. The geopolymer concrete specimens with 5% CFGC and 10% CFGC had the least compressive strength loss at 600 and 900 °C and were also the lightest colored. It was observed that the addition of ceramic

fibers to geopolymer concrete results in increased thermal durability and reduced surface burn damage. Among the geopolymer concretes tested, the specimen without ceramic fiber (0% CFGC) suffered the highest loss of compressive strength and exhibited the darkest color at 600 and 900 °C. This suggests that the thermal resistance of the 0% CFGC specimen is lower than that of the specimens with fiber addition. Therefore, it can be inferred that the burning damage on the surface is comparatively greater in the other specimens. This study highlights the fact that the ceramic fiber-added specimens exhibit significantly fewer crack formations and color changes after the high-temperature test in comparison to the other specimens.

Table 11. Appearances of the samples before and after the 900 °C high-temperature test.

	PCC	0% CFGC	2% CFGC	5% CFGC	10% CFGC
Before					
After					

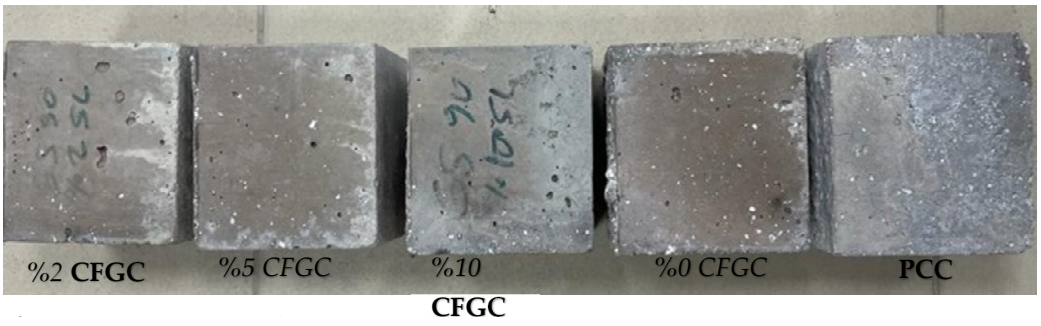


Figure 25. The views of 2%, 5%, 10% CFGC, 0% CFGC and PCC specimens after high temperature at 600 °C.

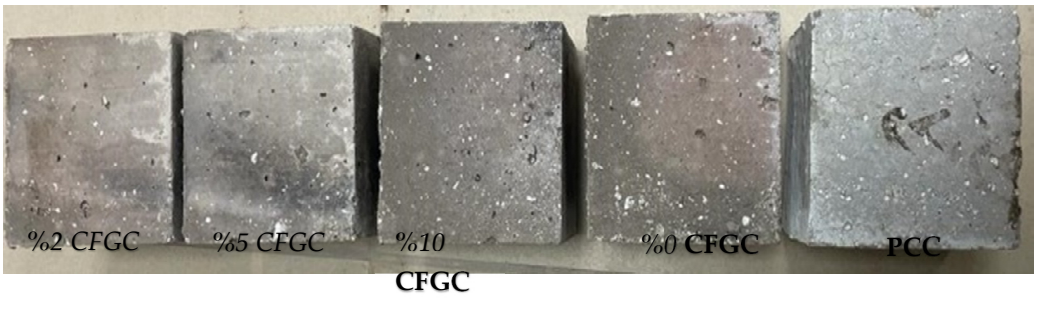


Figure 26. General view of 2%, 5%, 10% CFGC, 0% CFGC and PCC specimens after high temperature at 900 °C.

4. Conclusions

This study examines the impact of ceramic fiber on geopolymer concrete. Based on the data obtained, it can be observed that the

- The compressive strength tends to increase with higher slag content. The study found that an increase in slag content led to a decrease in workability and an increase in void ratio. However, the addition of 10% silica fume in place of slag in the GS90 specimen resulted in a higher compressive strength value due to the improved void ratio. The void ratio was reduced by approximately 1% with the use of reinforcement.
- Furthermore, ceramic fiber was added to the geopolymer concrete as a convenient material that dissolves easily.
- The ceramic fiber was evenly distributed throughout the internal structure of the geopolymer concrete, resulting in a significant reduction of the high-temperature effect.
- Upon examination of specimens exposed to high temperatures for 2 h, the compressive strength loss in the geopolymer specimens with added ceramic fiber decreased.
- After conducting a high-temperature test at 100 °C, it was observed that the compressive strength of 0% CFGC increased by 58.04%, 2% CFGC by 31.36%, 5% CFGC by 29.25%, and 10% CFGC by 53.40% compared to the initial strength. In contrast, PCC only experienced a 4.12% increase in compressive strength from its initial strength.
- Additionally, it was found that PCC retained its strength at room temperature following a high-temperature test at 300 °C. The compressive strength of geopolymer concrete specimens increased by significant percentages after being exposed to high temperatures. These results indicate the potential benefits of incorporating CFGC into geopolymer concrete.
- Specifically, the specimens containing 2%, 5%, and 10% CFGC showed approximately 30% higher compression strength values than PCC and 0% CFGC when measured after a high-temperature test at 600 °C. At 900 °C, it was observed that the strength of the specimens increased by approximately 2.5 times.
- It was noted that the compressive strength of the 0% CFGC specimens without adding PCC and ceramic fiber decreased to approximately 10 MPa at 900 °C. However, the 5% CFGC specimen maintained its compressive strength up to 24.4 MPa at this temperature.
- It was found that the addition of ceramic fiber to geopolymer concrete significantly reduced the decrease in concrete compressive strength by mitigating high-temperature damage.

The study suggests that the inclusion of ceramic fiber can improve the fire resistance of concrete. It is worth noting, however, that the study only examined the impact of ceramic fiber in geopolymer concretes. Additional research is required to explore the high-temperature performance of ceramic fiber in PCC and other concrete types.

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