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THE IMPACT OF FIRE FLAMES ON THE MECHANICAL CHARACTERISTICS OF BASALT FIBER-REINFORCED GEOPOLYMER CONCRETE COMPOSED OF SUSTAINABLE COMPONENTS

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Abstract. The use of geopolymer concrete (GPC) has been proposed to reduce carbon dioxide (CO_2) emissions linked to the cement production. Fire poses a significant risk to concrete structures, as it causes mechanical degradation of the concrete. This research used 70 % Granulated Ground Blast Furnace Slag (GGBFS) and 30 % Fly Ash (FA) to synthesis Geopolymer Concrete (GPC). The alkaline activation solution was created by mixing sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) at a concentration of 12 molarity. The ratio of the solution to the cementitious material was 0.4. The weight ratio of sodium silicate to sodium hydroxide was 2.5:1. Basalt fibres were used for reinforcement at volume fractions of 0.5 %, 0.75 %, and 1 %. The geopolymer concrete specimens were subjected to an elevated temperature of 70 °C in an oven for 4 hours, which is similar to the curing time of 2 days. After 56 days, the specimens were burned at three different temperatures of 300 °C, 500 °C, and 700 °C for one hour. The required tests (compressive strength, flexural strength, splitting tensile strength, and mass loss percentage) were conducted before and after the burning procedure. The residual compressive strength percentages obtained were 90 %, 73 %, and 61 %, the residual flexural strength percentages were 91 %, 70 %, and 51 %, the residual splitting tensile strength percentages were 89 %, 68 %, and 50 %, and the mass loss percentages were 1.271 %, 1.557 %, and 2.035 % for a 1 % ratio of basalt fibre at 300 °C, 500 °C, and 700 °C, respectively. Geopolymer concrete is highly resistant to flames, even at temperatures of up to 700 °C.

Keywords: Geopolymer concrete, granulated ground blast furnace slag, fly ash, sodium hydroxide, sodium silicate, basalt fibres.

1. Introduction

The production of clinker during cement manufacture, which emits one tonne of CO_2 for each tonne of clinker produced, accounts for 7 % of all global CO_2 emissions. Examining the technical and physical components of concrete that are environmentally friendly and reduce CO_2 emissions is essential. Using sustainable materials in civil engineering projects can reduce CO_2 emissions from cement production and improve the recycling of industrial waste, both of which are major causes of environmental damage (Wang, 2022). In order to overcome these deficiencies, significant efforts have been made to develop "geopolymers", which are an innovative and ecologically viable alternative to traditional Portland cement Lin et al. (2024). An increase in compressive strength is achieved by using geopolymer concrete with fly-ash-to-slag ratios of 80:20, 70:30, and 50:50, a curing temperature of 60 °C, and a ratio of alkaline solution to binder of 0.5. For the 50:50 ratio, it increased by 32 % and 40 % after curing periods of 7 and 28 days, respectively (Hussein and Fawzi, 2021).

Many studies have illustrated the synthesis of geopolymer concrete incorporating fly ash and slag. They used a low-molecular-weight sodium hydroxide solution to cure the concrete at room temperature. It is necessary to assess qualities like compressive strength, water absorption, and workability. Knowing what the mixture is made of is very important, especially the amounts of slag, sodium silicate (SS), and sodium hydroxide (SH), as well as some other important information. Slag was substituted by fly ash in 20 %, 30 %, 40 %, and 50 % of instances. The SH molarity was determined at 12 M, the SS/SH ratios were recorded as 1.0, 1.5, 2.0, and 2.5, and the activator-to-binder ratios were 0.40, 0.45, and 0.50 (Sang et al., 2023). Another study examined the fire performance of GPC compared with OPC-based concrete. The fly ash-based geopolymer concrete was exposed to a fire at temperatures of 500 °C and 1 200 °C for two hours using a methane burner torch. Specimens were used after 28 days of curing and then cooled to ambient temperature. The tests showed that the GPC became stronger when exposed to a fire at 500 °C, and lost less mass because less water evaporated during the process. The aim was to identify any signs of cracking, spalling, or discoloration. A comparison was conducted between the fire resistance of fly ash-based geopolymer concrete and ordinary Portland cement (OPC)-based concrete (Kumar et al., 2024). Real fire conditions were simulated by heating pieces with aver-

Oxide	Content [%]	ASTM C618-19 type F Requirement
Fe_2O_3	5.31	Sum of value more than 70 %
Al_2O_3	17.75	
SiO_2	64.73	
SO_3	0.26	Maximum 5 %
MgO	0.88	-
CaO	2.4	Maximum 18 %
K_2O	3.53	-
Na_2O	2.36	-
L.O.I.	2.9	Maximum 6 %

Table 1. Chemical specification of fly ash.

Physical properties	Fly ash	ASTM C618-19 type F Requirement
Amount retained sieved on 45 µm (No. 325) [%]	26.9	Max 34 %
Specific gravity	2.320	-
Surface area [$m^2\,kg^{-1}$]	570	-
Physical form	Powder	-

Table 2. Physical characteristics of fly ash.

age strengths of 20, 40, and 60 MPa for two hours at temperatures of 500 and 1 200 °C. Visual observation was used to assess mass loss and residual compressive strength, and Scanning Electronic Microscopic (SEM) and Fourier Transform In-Frared spectroscopy (FTIR) analyses were carried out. Significant cracking and spalling were observed for the OPC-based concrete, particularly in the high-strength specimen, whereas only minor cracking without spalling was observed for the geopolymer concrete. Compared to the OPC-based concrete, fires at 500 °C and 1 200 °C caused it to lose 1.69 % and 4 % its mass, respectively. It was found that geopolymers made from low- to medium-strength concrete were highly resilient in the same situation, which suggests they could be a better choice for fire-resistant applications. The material retained 50 % of its compressive strength following the exposure to fire at a temperature of 1 200 °C. The residual compressive strength of the geopolymer concrete increased from 13 % to 45 % after being exposed to a fire at a temperature of 500 °C for OPC-based concretes (Zhao and Sanjayan, 2011). Temperature greatly affects the slag/fly ash-based geopolymer mortar, as raising the temperature to 400, 600, and 800 °C for three hours decreased the mechanical properties of the conventional mortar, flexural strength by 20 %, 50 %, and 70 %, and compressive strength by 25 %, 45 %, and 65 %, respectively. The compressive strength of the slag-based GGBSF geopolymer mortar is 15 %, 20 %, and 30 % lower (Amar et al., 2023). The objective is to reduce global carbon emissions while simultaneously promoting the sustainable development and growth of the concrete industry. This involves advocating for environmental initiatives aimed at mitigating global warming and pollution, as well as producing geopolymer concrete from recycled waste materials such as fly ash and slag (GGBSF), which would otherwise end up in landfills.

The aim of this article is to study the influence of GGBSF and basalt fibre on the mechanical properties of reinforced geopolymer concrete following exposure to different temperatures during fire and in terms of thermal stability.

2. Materials and methods

2.1. Materials

2.1.1. Fly ash

The fly ash it was designed to be class F, according to the criteria established in ASTM C618-2019 as presented in Tables 1 and 2.

2.1.2. Granulated ground – blast furnace slag (GGBFS)

It is a by-product of the production process, generated by the rapid cooling of liquid iron by-product from a blast furnace using water or steam, at temperatures ranging from 1 500 °C to 1 600 °C, as stipulated by ASTM C618-2019 and shown in Tables 3 and 4.

2.1.3. Sodium hydroxide, NaOH

Commercially available sodium hydroxide flakes have a purity level of 98 %. Dissolving the solids in filtered

Oxide	Content [%]	ASTM C618-19 type F Requirement
Fe_2O_3	0.5	Sum of value more than 70 %
Al_2O_3	25.53	
SiO_2	45.88	
SO_3	1.98	Maximum 5 %
MgO	1.87	-
CaO	19.29	Maximum 18 %
K_2O	1.8	-
Na_2O	0.8	-
L.O.I.	2.53	Maximum 6 %

Table 3. Analysis of the chemical composition of GGBFS.

Physical properties	Fly ash	ASTM C618-19 type F Requirement
Amount retained sieved on 45 µm (No. 325) [%]	23.6	Max 34 %
Specific gravity	2.36	-
Surface area [$m^2\,kg^{-1}$]	400	-
Physical form	Powder	-

Table 4. Analysis of the physical composition of GGBFS.

Appearance	Result	Specification ASTM E291-09
(NaCl) [%]	0.09	0.15
($NaCO_3$)	0.38	0.39
(NaOH) min [%]	98.24	≤ 97.5
(FeO_3) max [%]	0.005	0.01
Nick as Ni^{+2}	2.52	5
Cu^{+2} [Ppm]	0.1	≤ 4
Na_2SO_3 [Ppm]	70	≤ 200
Water Insoluble [Ppm]	60	≤ 200
SiO_2 [Ppm]	14	≤ 20

Table 5. Chemical composition of sodium silicate.

water provides a concentrated solution, as detailed in the ASTM E291-2009 standard and shown in Table 5.

2.1.4. Sodium silicate, Na_2SiO_3

The required amount of Na_2SiO_3 was determined by comparing the quantities of sodium oxide, silicon dioxide, and H_2O.

2.1.5. Water

A mixture of distilled water was used to dissolve the caustic soda flakes in order to produce the sodium hydroxide solution. The addition of tap water, if required, conforms to IQS1703-2018.

2.1.6. Fine aggregate

Fine aggregate was used as zone 2, as specified in IQS (No.45-1984), as illustrated in Tables 6 and 7. The fineness modulus for the fine aggregate sample was 2.84.

Sieve [mm]	Accumulative passing [%]	IQS(NO.45/1980) Zone 2
10	100	100
4.75	93	90–100
2.36	80	75–100
1.18	71	55–90
0.6	52	35–59
0.3	23	8–30
0.15	6	0–10

Table 6. Fine aggregate sieve analysis.

2.1.7. Coarse aggregate

Deposits of river gravel and crushed stone can be found in these regions. In this experimental study, a coarse aggregate with a specific gravity value of 2.6 and a nominal size of 10 mm (as specified in IQS No.45-1984) is used, as shown in Table 8.

Physical Characteristic	Test Result	IQS(NO.45/1984)
Density [kg m^{-3}]	1 595	
Modules of fineness	2.75	
Specific gravity	2.65	
Absorption [%]	1.7	
Fine materials that traverse a 75 µm sieve	1.4	Max of 5 %
Sulfate content [%]	0.15	Max of 0.5 %

Table 7. Physical and chemical properties of the fine aggregate.

Sieve [mm]	Accumulative passing [%]	Limit of IQS(NO.45-1980) nominal size 10 mm
14	100	100
10	93	85–100
4.75	6	0–25
2.36	1	0–5

Table 8. Coarse aggregate grading.

2.1.8. Basalt fibre reinforcement

Natural volcanic ejecta is the source of basalt fibre, an inorganic fibre material that is processed at high temperatures of 1 500–1 700 °C, as shown in Table 9.

2.1.9. Super-plasticizers

Superplasticisers improve the workability, flexural and compressive strength, and reduce shrinkage of concrete. The recommended dosage is 0.5–2.5 kg per 100 kg of cement, in accordance with the requirements of ASTM C494-13 Type G, as evidenced by the data presented in Table 10.

Characteristics	Value
Chopped diameter [µm]	13
Chopped length [mm]	12
Tensile strength [MPa]	2 600–4 840
Specific gravity	2.6–2.8

Table 9. Properties of basalt fibre according to the data manufacturing.

Characteristics	Value
Structure of the Material	Polycarboxylic
Density at 20 °C [kg l^{-1}]	1.082–1.142
Alkaline Content [%]	< 3

Table 10. Properties of super-plasticiser according to the data manufacturing.

3. Geopolymer concrete design

3.1. Preparation of alkaline solution

In this experiment, a molar concentration of 12 moles of sodium hydroxide was used in the production of geopolymer concrete. After mixing and cooling the composite, the sodium silicate was added. The activated solution was left for 24 hours with a ratio of 2.5:1 between the sodium silicate and the sodium hydroxide. The ratio of the solution to the cementitious components was 0.4.

3.2. Mixing and moulding of specimens

The alkaline solution was combined with the superplasticiser prior to application. The dry constituents (GGBFS at 70 % and FA at 30 %) were mixed manually for 2 minutes before the alkaline liquid including all additives, was added, as shown in Table 11. This process was repeated with 2 % superplasticiser and 10 % tap water according to the type of binder used. Homogeneity was achieved after 10–15 minutes. An electric mixer was used for mixing. Concrete layers were applied to moulds in accordance with ASTM C192-2019, and the specimens were compressed and smoothed to achieve a consistent humidity levels.

3.3. Curing

In accordance with ASTM. C192/C192M-19, the specimens were placed in an oven at a temperature of 70 °C for four hours for two days, one day after the casting. The specimens were tested at 56 days in order to simulate the behaviour of GPC when exposed to fire in real conditions.

4. Methods

4.1. Effect of fire on the mechanical properties of GPC

According to the firing curve (time-temperatures curve) in ASTM E119-00a-(2000), the specimens were burned at temperatures of 300, 500, and 700 °C for one hour at each temperature, until the temperature reached a stable state. Then, it continues for the duration specified in previous studies Kannangara et al. (2021), as illustrated in Figure 1. The re-

Mix type	FA slag	Slag	FA	Na_2SiO_3	NaOH	Coars agg.	Fine agg.	Basalt fiber [%]
GR	30:70	525	225	214	85.5	945	728	0
G1	30:70	525	225	214	85.5	945	728	0.5
G2	30:70	525	225	214	85.5	945	728	0.75
G3	30:70	525	225	214	85.5	945	728	1

Table 11. GPC mix for $1\,\mathrm{m}^3$, weight in $\mathrm{kg\,m^{-3}}$.


(A). Burning specimens by fire flame.
(B). Measuring temperatures with thermocoupling.

Figure 1. The process of burning specimens with a flame and at different temperatures in the burning furnace.

quired tests (compressive strength, flexural strength, splitting tensile strength, and mass loss) were conducted after burning.

4.1.1. Compressive strength

A compressive strength test of GPC was conducted in accordance with BS-EN-12390-3:2019. Using a cube with dimensions of $100\,\mathrm{mm}^3$, the test was performed using a hydromechanical testing apparatus with a loading rate of 2 000 kN and $2.5\,\mathrm{MPa\,s^{-1}}$. Compressive strength was calculated using equation:

$$f_c = \frac{P}{A_c}, \tag{1}$$

where:

f_c Compressive Strength [MPa],

P maximum applied load [N],

A_c cross-sectional area [mm^2].

4.1.2. Flexural strength test

This test was conducted in accordance with ASTM C293-2002 to evaluate the flexural strength of the GPC under a one-point load. Prism specimens measuring 380 × 80 × 80 mm were used, after curing for 56 days. Flexural strength was calculated using equation:

$$R = \frac{3pl}{2bd^2}, \tag{2}$$

where:

R Flexural value [MPa],

p maximum load [N],

l length of the span [mm],

b average width of a specimen [mm],

d average prism thickness depth [mm].

4.1.3. Splitting tensile test

Three cylinders with dimensions of 100 × 200 mm were used, in accordance with ASTM C496-2017. The test was conducted using a hydraulic compression apparatus at 2 000 kN, which determined the tensile strength using equation:

$$f_{\mathrm{sp}} = \frac{2p}{\pi dl}, \tag{3}$$

where:

f_{sp} Indirect tensile strength [MPa],

p maximal load applied, as indicated by the testing machine [N],

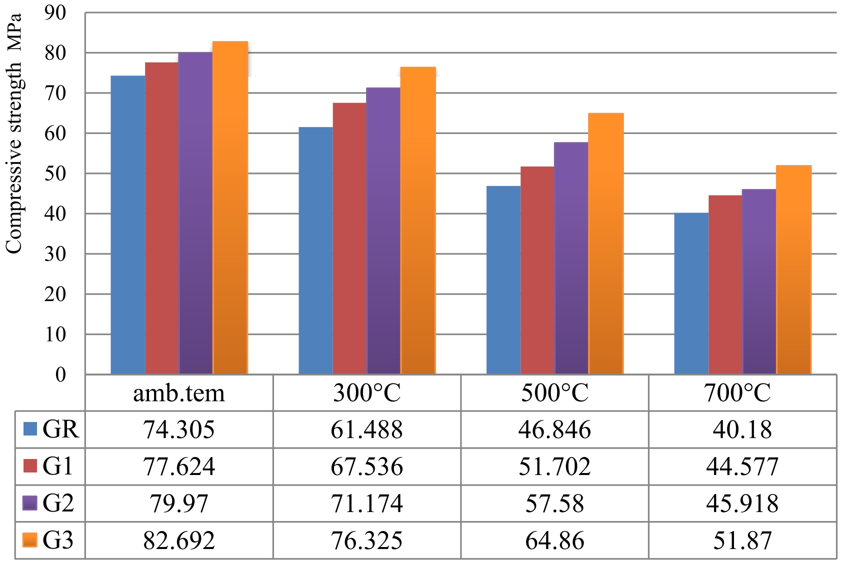
d cylinder diameter [mm],

l cylinder length [mm].

5. Results and discussion

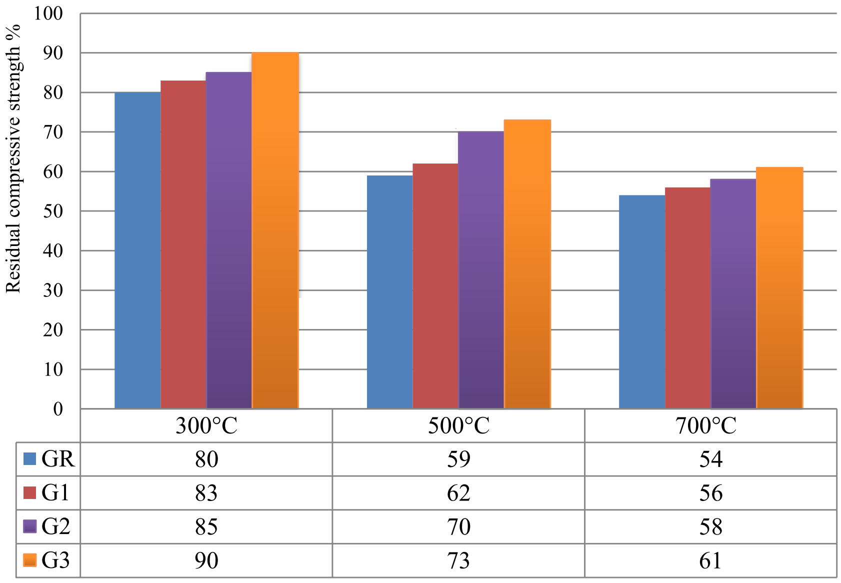
5.1. Residual compressive strength

The compressive strength test results for GPC specimens after exposure to fire are summarised in Figure 2. Figure 3 shows the percentage residual compressive strength values for GPC mixes subjected to fire at various temperatures (300, 500, and 700 °C). At 300 °C,



	amb.tem	300°C	500°C	700°C
■ GR	74.305	61.488	46.846	40.18
■ G1	77.624	67.536	51.702	44.577
■ G2	79.97	71.174	57.58	45.918
■ G3	82.692	76.325	64.86	51.87

Figure 2. Compressive strength results after burning at varying temperatures.



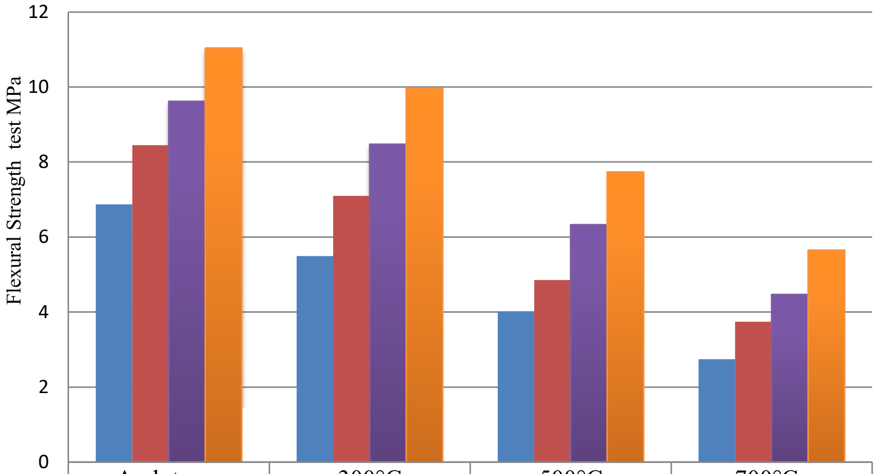
	300°C	500°C	700°C
■ GR	80	59	54
■ G1	83	62	56
■ G2	85	70	58
■ G3	90	73	61

Figure 3. Percentage residual compressive strength test results.

the percentage residual compressive strength values of the GPC mixes were 84 %, 87 %, 89 %, and 92 % for GR, G1, G2, and G3, respectively, compared to the same mixes before the exposure to fire. Raising the temperature to 500 °C, the percentage residual compressive strength values of the GPC mixes were 64 %, 67 %, 72 %, and 76 % for GR, G1, G2, and G3, respectively, compared to the same mixes before the exposure to fire. Further loss of compressive strength occurred when specimens were burnt at 700 °C. In this case, the percentage residual compressive strength values of the GPC specimens were 54 %, 56 %, 58 %, and 61 % for GR, G1, G2, and G3, respectively, compared to the same mixes before the exposure to fire. These results are consistent with those of Awad (2020). GPC with GGBFS shows a superior fire resistance, maintaining structural integrity at temperatures of up to 700 °C, the presence of silica and alumina in the material increases thermal stability, reducing thermal shrinkage. It is also the mechanism of GGBFS forming denser structure that slows down the propagation of cracks when exposed to fire, as confirmed by Ghanem and Awad (2024). Basalt fibres have can improve the residual compressive strength of GPC even in the event of fire.

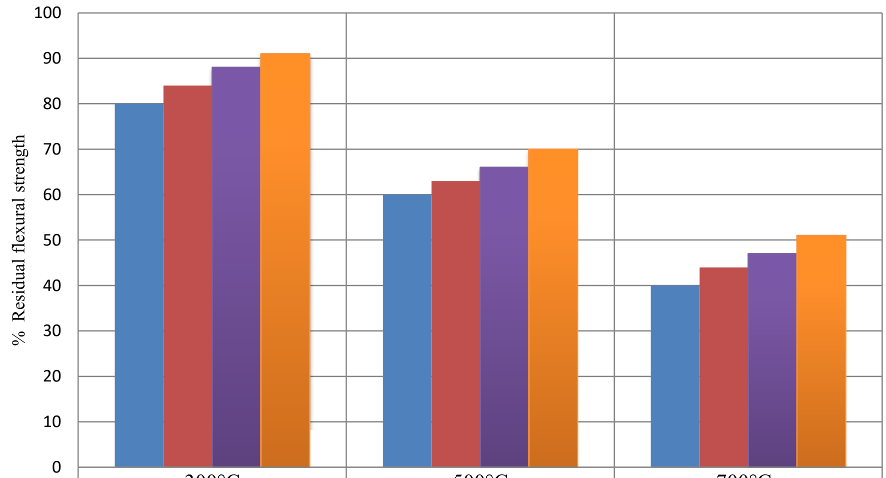
5.1.1. Residual flexural strength

The flexural strength test results for GPC specimens exposed to fire are summarised in Figure 4. The results indicated that flexural strength decreased as the burning temperature increased for all GPC specimens. Figure 5 shows the percentage residual flexural strength values for GPC mixtures exposed to fire at various temperatures (300 °C, 500 °C, and 700 °C). At 300 °C, the percentage residual flexural strength values for GPC specimens was 80 %, 84 %, 88 % and 91 %.



	Amb.temp	300°C	500°C	700°C
🟦 GR	6.868	5.494	4.017	2.747
🟥 G1	8.448	7.1	4.851	3.741
🟪 G2	9.615	8.472	6.327	4.467
🟧 G3	11.036	9.964	7.732	5.649

Figure 4. Effect of different burning temperatures on the flexural strength for all mixes.



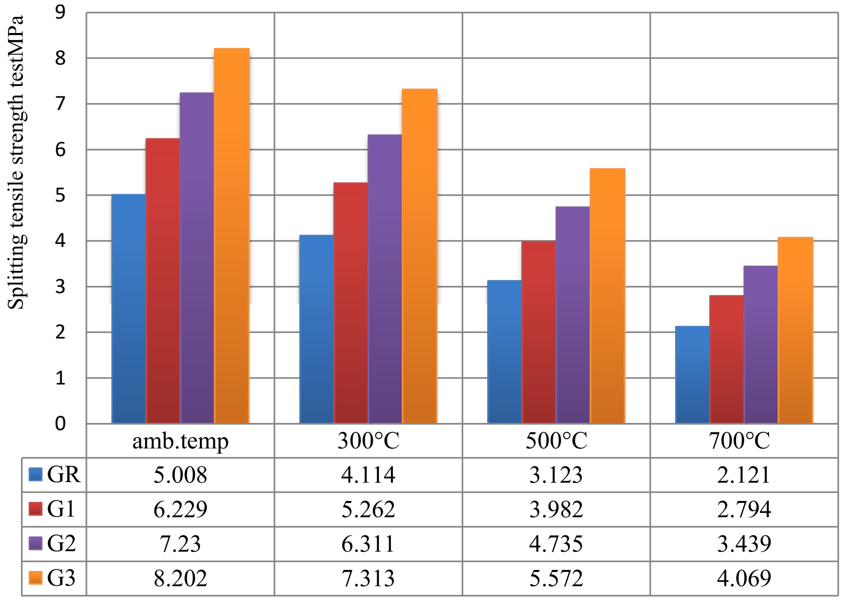
	300°C	500°C	700°C
🟦 GR	80	60	40
🟥 G1	84	63	44
🟪 G2	88	66	47
🟧 G3	91	70	51

Figure 5. Percentage residual flexural strength.

for GR, G1, G2, and G3, respectively. At 500 °C, these values decreased to 60 %, 63 %, 66 %, and 70 % for the same mixes. A further decrease was observed at 700 °C, with the specimens losing 40 %, 44 %, 47 %, and 51 % of their flexural strength. This is due to a decrease in bending resistance and weakening of bonds in the geopolymeric structure. The increased porosity of the material leads to tiny fractures due to vapour pressure (Aboud et al., 2024). At 500 °C, the chemical linkages break down, leading to the partial disruption of the Si-O-Al and Si-O-Si bonds and the creation of small cracks due to thermal stresses, which decreases flexural strength by approximately 30–50 %. At 700 °C, the material undergoes recrystallisation, resulting in significant structural changes from glassy to crystalline. GPC specimens that included BF showed an increase in their residual flexural strength from the previous measurement after the fire exposure due their strong pull-out strength (Alzeebaree et al., 2021; Mohamed and Zuaiter, 2024).

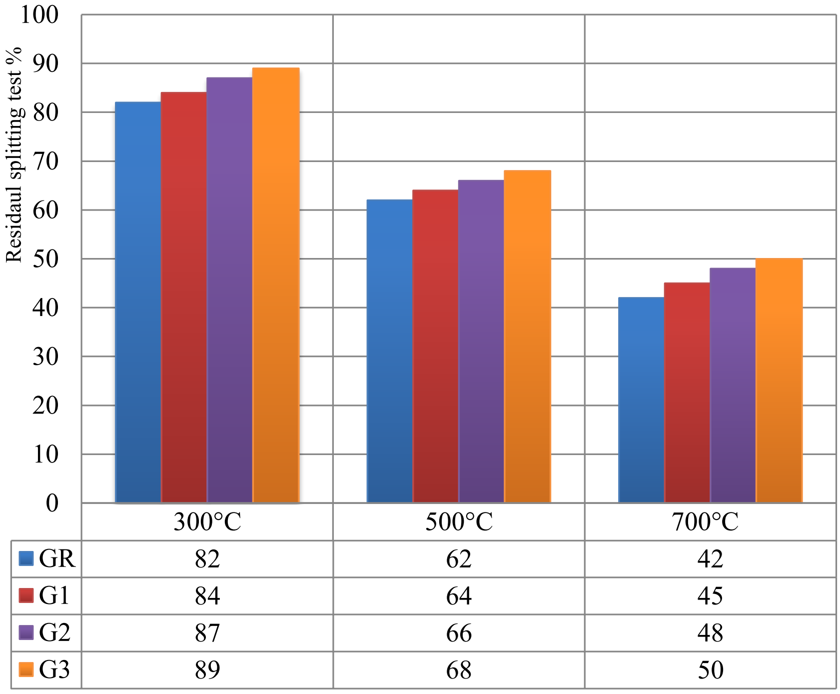
5.1.2. Residual splitting tensile strength test

Figures 6 and 7 present the results of the splitting tensile strength test, showing the percentage of residual splitting tensile strength for GPC exposed to fire at varying temperatures of 300 °C, 500 °C, and 700 °C. The findings demonstrated that the splitting tensile strength decreased as the temperature increased for



	amb.temp	300°C	500°C	700°C
GR	5.008	4.114	3.123	2.121
G1	6.229	5.262	3.982	2.794
G2	7.23	6.311	4.735	3.439
G3	8.202	7.313	5.572	4.069

Figure 6. Relationship between different temperatures of fire and splitting tensile strength.



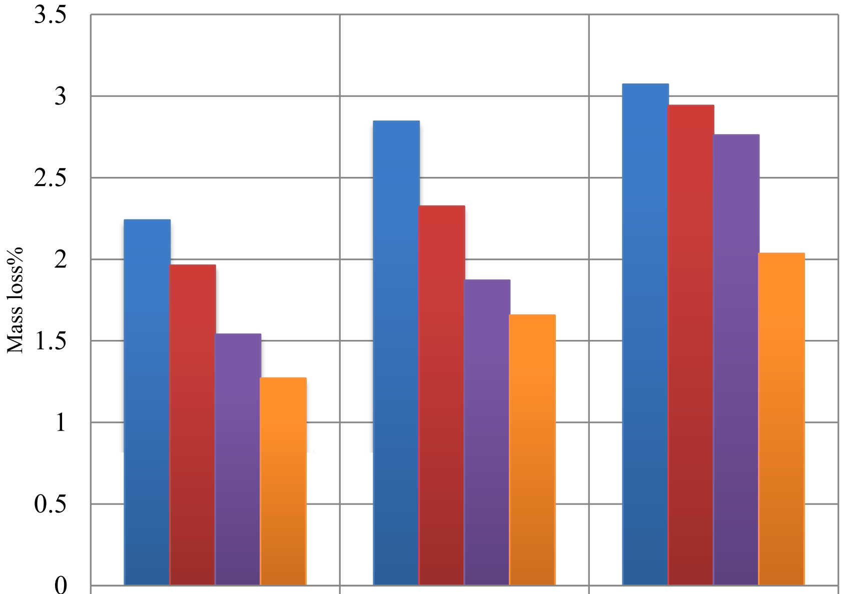
	300°C	500°C	700°C
GR	82	62	42
G1	84	64	45
G2	87	66	48
G3	89	68	50

Figure 7. Relationship between residual splitting tensile strength at different temperatures.

all GPC specimens. At 300 °C, the percentage residual splitting tensile strength was 82 %, 84 %, 87 %, and 89 % for GR, G1, G2, and G3, respectively, compared to their initial strength. At 500 °C, the value decreased to 62 %, 64 %, 66 %, and 68 %. A further decrease was observed at 700 °C, with the specimens losing 42 %, 45 %, 48 %, and 50 % of their strength. At 300 °C, the initial reduction in tensile strength was attributed to the loss of chemical moisture. At 500 °C, however, the reduction of 25–40 % was due to the breakdown of GPC bonds. At 700 °C, a significant decrease in tensile strength 50–70 % was observed due to the degradation of the GPC binder, with different percentages of fibres affecting the performance. The fibres help to delay fracture during combustion, thereby enhancing the overall strength when exposed to fire (Natarajan and Vellaipandian, 2023).

5.1.3. Mass loss

To determine mass loss, the weight of the concrete cubes was measured before and after the exposure to fire. Figure 8 shows the effects of heating geopolymer concrete samples to 300 °C, 500 °C, and 700 °C for one hour. The mass loss is relative to their initial mass at 56 days after casting. When water evaporates from its bound and unbound forms inside the concrete matrix, it severely damages the specimens



	300°C	500°C	700°C
🟦 GR	2.24	2.845	3.072
🟥 G1	1.963	2.325	2.942
🟪 G2	1.54	1.871	2.761
🟧 G3	1.271	1.657	2.035

FIGURE 8. Relationship between percentage mass loss results and different fire temperatures.

and causes them to lose mass. At 300 °C, the evaporation of free and chemically bound water with minor decomposition of geopolymer gel occurs. At 500 °C, further dehydration and breakdown of Al-Si gel as well as structural and micro cracking begin to show. At 700 °C, an even greater mass loss and microcracking occurs, because the increase in combustion temperature causes a greater increase in mass loss than in traditional concrete, which has a very high mass loss. Geopolymer concrete has superior fire resistance even at temperatures of up to 700 °C, there is no spalling and remains cohesive. The volume ratio of GGBFS which makes the GPC resistant to fire is 0.4, as confirmed by Kilma et al. (2022). The incorporation of basalt fibres into geopolymer concrete has been shown to influence mass loss, particularly under high-temperature conditions, as it improves the mechanical properties and thermal stability of the GPC (Robert et al. 2023).

6. CONCLUSION

The GPC with the GR mix, which does not contain basalt fibres, is fire-resistant at temperatures of 300 °C, 500 °C, and 700 °C. The G1, G2, and G3 mixtures that containing 0.5 %, 0.75 %, and 1 % basalt fibres, respectively, exhibit even better fire resistance at the same temperatures, in addition to thermal stability and resilience. The compressive strength test results for the GR, G1, G2, and G3 mixtures obtained before exposure to fire were 74.305, 77.628, 79.970, and 82.692 MPa, respectively, While the compressive strength of the same mixes reached 40.180, 44.577, 45.918, and 51.870 MPa at the highest fire temperature of 700 °C, These results clearly demonstrate the effectiveness of concrete reinforced with basalt fibres, which provide high resistance to burning temperatures. The percentage residual compressive strength values were 90 %, 73 %, and 61 %, the percentages of flexural strength were 91 %, 70 %, and 51 %, and the percentage residual of splitting tensile strength values were 89 %, 68 %, and 50 % for G3 at 300 °C, 500 °C, and 700 °C, respectively. This evidence highlights the importance of using basalt fibres, which protect concrete components from burning and provide outstanding flexural and tensile resistance performance. The mass loss of GPC specimens after exposure at 300, 500, and 700 °C are 1.054 %, 1.250 %, and 1.469 % for G3, respectively. Microcracking begins at 500 °C, at 700 °C it shows a greater mass loss than its predecessor, and microcracking can be seen. Geopolymer concrete is highly fire-resistant, does not spall and appears cohesive even at temperatures of up 700 °C. The GGBFS components improve heat stability and preserve structural integrity at this temperature. Basalt fibre-reinforced geopolymer concrete is an excellent fire-resistant material and has demonstrated thermal stability. The optimal fibre content was found to be 1 %.

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