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Research Paper

Influence of Aggregate Type and Size on Residual Mechanical Properties of Post-Heated Geopolymer Concrete: Experimental Study and Applications of Artificial Neural Networks

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ABSTRACT

To mitigate environmental impacts from Portland cement (PC) production, the researcher's efforts is introducing eco-friendly alternatives such as Geopolymer concrete (GPC). While GPC shows promise, further research is required to understand how fire or elevated temperatures affect GPC's mechanical properties. This research investigates the effects of elevated temperatures (200°C, 400°C, 600°C, and 800°C) on the residual mechanical properties (compressive, flexural, splitting-tensile strengths, and modulus of elasticity) of ambient-cured fly-ash (FA)-based GPC compared to PC mixtures. The study examined various concrete types (GPC and PC), three coarse aggregate types (basalt, gravel, and crushed dolomite), and three crushed dolomite sizes (40 mm, 20 mm, and 14 mm). Additionally, Artificial Neural Network (ANN) models were developed to predict the residual compressive strength of both ambient-cured and heat-cured GPC after exposure to elevated temperatures. Results showed that basalt aggregate significantly enhanced the residual mechanical properties at 800 °C, outperforming crushed dolomite and gravel in compressive, flexural, splitting-tensile strengths, and modulus of elasticity, with increases of (20%, 80%), (26%, 244%), (10%, 100%), and (14%, 140%), respectively. Moreover, the residual mechanical properties were found to be inversely proportion with max size of coarse aggregate. In addition, using ANN models proved its efficient in predicting the compressive strength for both ambient and heat-cured GPC with R² values of 0.94 and 0.887, respectively.

1 Introduction

Climate change has emerged as a critical global challenge, with severe environmental consequences such as river desiccation and disruptions to agricultural systems. Therefore, drastic actions must be taken otherwise, in the future, adapting to these impacts will be more difficult and more costly. Concrete is the most common construction material since it has many benefits, including low cost, ease of manufacture, acceptable strength, good durability, good fire resistance, and non-

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combustibility characteristics [1]. Cement production significantly contributes to global warming as Portland cement (PC) industry causes the emission of many pollutant gases, such as carbon dioxide (CO₂) [2] and [3]. The manufacturing of PC is responsible for about 5%-8% of CO₂ emissions every year around the world [4, 5] which causes irreversible environmental damages [6]. Global demand for PC is expected to increase by more than 12% until 2050, due to the increase in world population and the needs of infrastructure development [4]. In order to limit the release of CO₂ emissions, different binders and raw materials can be developed and used as alternatives to cement, as a partial or full replacement, to produce eco-friendly concrete [7].

Geopolymer Concrete (GPC), an alternative to Portland cement concrete (PCC), offers potential sustainability benefits [7-10]. Recently, GPC has garnered significant research interest due to its superior properties, including low carbon emissions, high early strength, excellent durability, and fire resistance [6, 11-18]. Geopolymers (GP) mainly consists of two types of materials namely aluminosilicate solids (silica fume (SF), fly ash (FA), metakaolin (MK), ground granulated blast furnace slag (GGBS) etc.) [19] and alkaline activating solutions [20]. Most common activating solutions include sodium silicate (Na₂SiO₃), sodium hydroxide (NaOH), potassium silicate (K₂SiO₃) and potassium hydroxide (KOH) [21]. The dissolved Al₂O₃ and SiO₂ species undergoes geopolymerization to form a three-dimensional amorphous alumina-silicate network that have strength similar or higher than that of PCC [6] and [22].

Fire safety is a critical consideration in structural design. PCC is widely used in construction due to its non-combustible nature and fire resistance. However, PCC exhibits vulnerabilities such as cracking, spalling, and strength loss under fire conditions [21]. In contrast, GPC demonstrates superior fire resistance compared to PCC [23-25]. Many researches have studied the performance of GPC after exposure to high temperatures [25-33]. Residual compressive strength of GPC and GP mortars with steel fibers was higher than that of GPC and GP mortars without steel fibers after exposure to high temperatures [34]. Junaid et al. [35] found that the strength loss is between 40 and 50% for GPC specimens when subjected to elevated temperatures up to 1000 °C. Kong and Sanjayan [24] found that the residual strength of FA-based GPC was 41.5% after exposure to 800 °C. PCC specimens suffered severe spalling, while there was no spalling in GPC specimens after exposure to 800 °C and 1000 °C [27]. Bond properties of GPC were found to be better than PCC after exposure to elevated temperatures [26].

Curing significantly influences GPC's setting time and properties, as it governs molecular network formation and ensures optimal mechanical and durability performance [36]. To activate the geopolymerization process of alumina-silicate in FA-based geopolymers, a moderate heat (60 to 90 °C) is required to [22, 37]. As a result, to achieve this heat, a steam curing chamber or oven is needed which limits the in-situ application of GPC [38]. In addition, heat curing also negatively affects the carbon footprint [38]. heat-cured FA-based GPC exhibited good fire resistance and residual mechanical properties after exposure to elevated temperatures [27, 30, 32, 39]. Several studies have focused on using GGBS with ambient cured FA-based GP to reduce the setting time and to improve the early-age compressive strength [40]. Compressive strength of GPC containing 20% GGBS and 80% FA reached 51 MPa at ambient curing [41]. Guerrieri and Sanjayan [42] found that using 35% GGBS as a replacement of FA achieved the highest compressive strength either at ambient temperature or after exposure to elevated temperature. ambient cured FA-based GP containing 20% GGBS showed a reduction of about 62% in the compressive strength after exposure to 1000 °C [43]. Residual compressive strength of GP mortar containing 50% GGBS and 50% FA was 91.7% after exposure to elevated temperatures up to 600 °C [44]. The residual compressive strengths of GPC containing GGBS were 114%, 88%, 32% and 25% after exposure to 400 °C, 600 °C, 800 °C, and 1000 °C, respectively [45]. Ramagiri et al., [46] showed that GPC made with FA/GGBS ratio of 70/30 exhibits the best mechanical performance after exposure to elevated temperatures.

Laboratory testing of concrete mechanical properties is time-consuming and resource-intensive [47, 48]. In addition, the mechanical properties of PCC or GPC are affected by different factors (such as content and types of binder material, weights of fine and coarse aggregates, fineness modulus of fine aggregate, nominal size of coarse aggregate, water or alkaline solution content, curing time, curing conditions, age of specimens.... etc.) which could make the optimum or accurate estimation more difficult [47]. Artificial Intelligence (AI) techniques have been widely used in construction field such as designing self-compacting concrete mixes [49] and predicting the mechanical properties and behavior of PCC [50-52] and GPC [53, 54]. Studying the behavior of PCC or GPC after exposure to high temperatures consumes a lot of time, effort, and high cost. Therefore, using AI in predicting mechanical properties of concrete becomes an urgent necessity. Gupta et al., [55], Abbas et al., [56], Ghazy et al., [57] and Liu et al., [58] proposed Artificial Neural Network (ANN) models to predict mechanical properties, fire resistance and temperature distributions for different types of PCC. When GPC is exposed to elevated

temperatures, its physical and mechanical properties change due to loss of moisture, decomposition of aggregate. Most of previous studies focused on predicting the properties and behavior of GPC in conventional conditions (i.e, ambient temperature) based on mixture composition. However, the prediction of residual compressive strength of GPC mixes after exposure to high temperatures has been less considered [59].

According to the previous review, numerous studies have been conducted to study the performance of heat-cured GPC taking into consideration many factors such as alkaline solution type, molarity of hydroxide solution, incorporating GGBS and time of fire exposure. However, limited studies focused on the effect of coarse aggregate types and sizes on the performance of ambient-cured GPC after exposure to elevated temperatures. Also, very limited research has been done in predicting the residual compressive strength of GPC after exposure to high temperatures using ANN applications. So, this investigation aims to study the physical and mechanical properties of ambient-cured GPC mixes after exposure to elevated temperatures taking into consideration two variables; first is the binder materials and second is the coarse aggregate types and sizes. FA-based GPC and FA/GGBS-based GPC were produced to study the effect of using GGBS on the residual mechanical properties of ambient-cured GPC mixes after exposure to elevated temperatures. Also, three different types (Basalt, crushed Dolomite and Gravel) and three different max-sizes (14 mm, 20 mm, and 40 mm) of coarse aggregate were used to study their effect on the residual mechanical properties of ambient-cured GPC mixes after exposure to elevated temperatures. Moreover, as AI can save time and cost in performing experimental works, ANN was implemented to predict the residual compressive strength of both heat-cured and ambient-cured GPC after exposure to elevated temperatures.

2 Experimental work

2.1 Materials

Low-calcium Fly Ash (FA) class F as specified in ASTM C618 [60] with a specific gravity of 2.4 was used as the main aluminosilicate material to manufacture geopolymer concrete (GPC) mixes. Ground granulated blast furnace slag (GGBS) with a specific gravity of 2.9 was used in some GPC mixes. Portland cement (PC) CEM1 42.5N complied with the requirements of EN 196-1 [61] and ES 4756-1 [62] was used in PC concrete (PCC) mixes. Results of the X-ray fluorescence (XRF) test performed on the used FA, GGBS and PC are shown in Table 1.

The used alkaline activator consisted of 14M potassium hydroxide (KH) [17], and sodium silicate solution (NS), with chemical compositions of 14.7% Na₂O, 29.4% SiO₂, and 55.9% water by mass. The NS/KH ratio was 2.5. Tap water complied with the requirements of the ECP 203-2019 [63] was used for preparing the hydroxide solution, mixing and curing PCC specimens.

Table 1- Chemical composition of FA, GGBS and PC

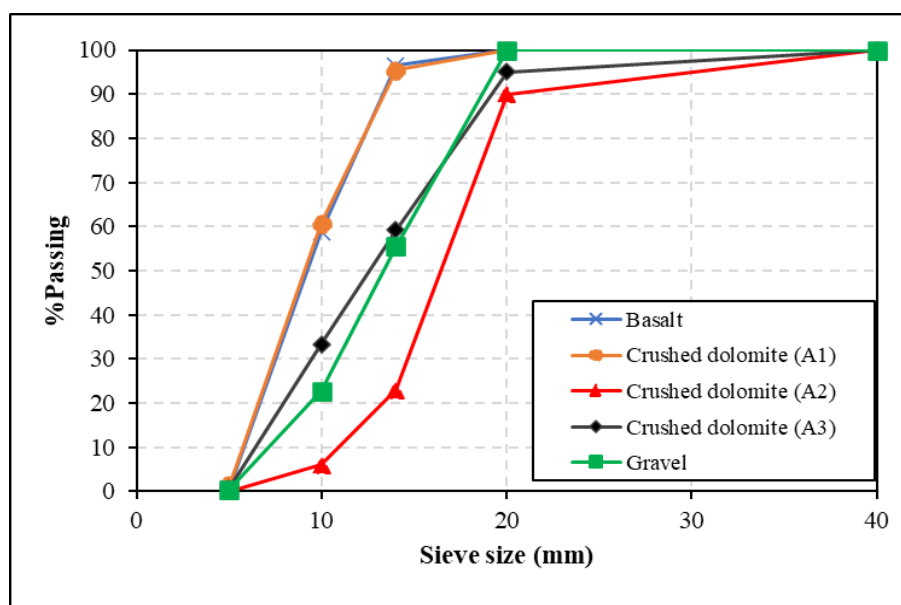
Compound	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	K ₂ O	MgO	P ₂ O ₅	SO ₃	MnO ₂	LoI
FA	60.50	27.97	5.55	1.99	0.21	1.28	0.64	0.59	0.24	0.03	0.89
GGBS	37.87	14.01	1.67	39.54	0.17	0.50	4.38	0.01	1.31	0.40	2.00
PC	21.50	5.15	3.45	63.41	0.43	0.25	0.87	0.003	2.95	0.001	1.83

The fine aggregate used was medium well graded siliceous sand, complied with the requirements of ASTM C33 [64], having a fineness modulus of 2.4 and specific gravity of 2.55. Three types of coarse aggregates complied with the requirements of ECP 203-2019 [63] were used, namely crushed basalt (B), crushed dolomite (A), and gravel (G). To study the effect of coarse aggregate size, three different sizes of crushed dolomite were used (A1), (A2), and (A3) as shown in Table 2. The physical and mechanical properties of fine and coarse aggregates are presented in Table 2. Moreover, the grain size distribution curves of the used coarse aggregates are shown in Fig. 1.

Table 2- Physical and mechanical properties of the fine and coarse aggregates

Property	Sand	Basalt (B)	Crushed Dolomite			Gravel (G)
			(A1)	(A2)	(A3)*	
Specific gravity	2.55	2.85	2.60	2.65	2.62	2.60
Unit weight (t/m ³)	1.75	1.80	1.58	1.62	1.60	1.70
Void ratio %	31.37	36.80	39.20	38.86	38.93	34.60
Fineness modulus	2.40	5.60	5.18	6.77	6.71	5.50
Crushing index, %	-	10.10	22.00	23.40	22.50	14.70
Clay and fine content, %	0.50	0.80	0.95	0.96	0.96	0.60
Water absorption %	0.9	0.85	1.1	1.2	1.1	0.72
Maximum nominal size (mm)	-	14	14	40	20	20

* Where A3 is a mix of A1 and A2 with a ratio of 50/50

**Figure 1 - Grading of the used coarse aggregates**

2.2 Mix proportions and specimens preparation

Fifteen mixes—divided into three groups—were prepared to evaluate the effects of elevated temperatures (200–800°C) on GPC and PCC. Group 1 comprised FA-based GPC, Group 2 included FA/GGBS-blended GPC, and Group 3 contained PCC with a 30 MPa design strength. To study the effect of coarse aggregate types and sizes, five mixes of concrete were designed in each group using absolute volume method. **Table 3** presents the constituents of different GPC and PCC mixes. For GPC mixes, a 14M KOH solution was prepared 24 hours prior to mixing. NS was added to the KOH solution 2 hours before mixing to form the alkaline activator.

To assure the homogeneity of the concrete mixture, the binder materials, sand, and coarse aggregates were first dry mixed together in a mechanical drum type concrete mixer, with capacity of 100 liter, for 2 min. The alkaline solution was then added, and all constituents were blended again for at least 5 min until the mixture became glossy and well-combined. The same procedure was followed in preparing PCC mixes.

All GPC and PCC samples were cast and compacted for 60 s on a vibrating table. Each mix included 15 cubes 100x100x100 mm, 15 prisms 100x100x500 mm and 30 cylinders 100x200 mm. PCC specimens were covered with plastic

sheets, stored in molds at $25 \pm 2^\circ\text{C}$ and 50% relative humidity for 24 hours, demolded, labeled, and water-cured at 20°C for 28 days. GPC specimens were covered, stored in molds at $25 \pm 3^\circ\text{C}$ and 50% relative humidity for 3 days, demolded, labeled, and ambient-cured outdoors for 90 days. The outdoor temperature profile for the curing duration is shown in **Fig. 2**.

Table 3 - Mix proportions of GPC and PCC kg/m³

Group	Mix ID	FA	GGBS	PC	Sand	Basalt (B)	Crushed Dolomite		Gravel (G)	NS	KH	Water
							(A1)	(A2)				
Group 1	FB1	400	-	-	666	1086	-	-	-	134	54	-
	FA1	400	-	-	666	-	1086	-	-	134	54	-
	FA2	400	-	-	666	-	-	1086	-	134	54	-
	FA3	400	-	-	666	-	543	543	-	134	54	-
	FG	400	-	-	666	-	-	-	1086	134	54	-
Group 2	FSB1	300	100	-	670	1092	-	-	-	134	54	-
	FSA1	300	100	-	670	-	1092	-	-	134	54	-
	FSA2	300	100	-	670	-	-	1092	-	134	54	-
	FSA3	300	100	-	670	-	546	546	-	134	54	-
	FSG	300	100	-	670	-	-	-	1092	134	54	-
Group 3	CB1	-	-	400	655	1060	-	-	-	-	-	188
	CA1	-	-	400	655	-	1060	-	-	-	-	188
	CA2	-	-	400	655	-	-	1060	-	-	-	188
	CA3	-	-	400	655	-	530	530	-	-	-	188
	CG	-	-	400	655	-	-	-	1060	-	-	188

Where: FA fly ash, GGBS ground granulated blast furnace slag, PC Portland cement, NS sodium silicate solution, KH potassium hydroxide solution with 14M.

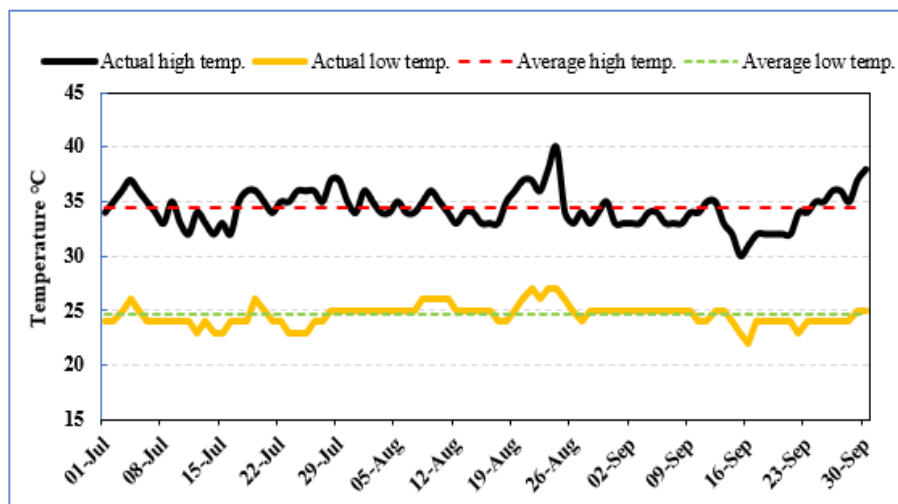


Figure 2 - Outdoor temperature during the period from March to May 2022

2.2.1 Elevated Temperature regime

All PCC and GPC specimens were exposed to elevated temperature at the age of 90 days after casting. Specimens were heated in an electrical heater furnace with capacity up to 1200°C . For each mix, three cubes, three prisms and six cylinders

were exposed to 200 °C, 400 °C, 600 °C, and 800 °C according to the elevated temperature rate as shown in Fig. 3. The furnace temperature was controlled to approximately follow the ISO834 curve. The temperature was sustained at the target temperature for 2 h [25, 65] then, specimens were allowed to cool naturally inside the furnace. Figure 4 shows the specimens inside the furnace.

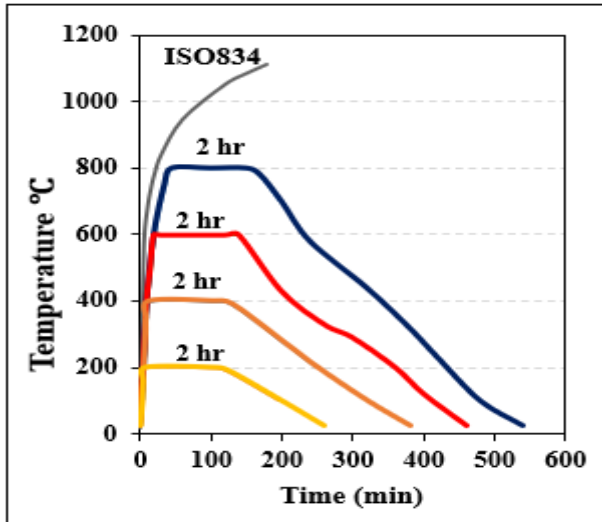


Figure 3 - Elevated temperature curve



Figure 4 - Concrete specimens inside the furnace

2.2.2 Physical tests

The average weight of three cube samples from each mix were taken before and after exposure to 200 °C, 400 °C, 600 °C, and 800 °C to determine the percentage of weight loss as a physical test. The percentage of weight loss of PCC and GPC specimens was calculated by dividing the loss in weight after exposure to elevated temperature by the original weight.

2.2.3 Mechanical tests

Compressive, flexural, splitting strengths and modulus of elasticity of GPC and PCC specimens were measured at the age of 90 days before and after exposure to elevated temperatures of 200 °C, 400 °C, 600 °C, and 800 °C. Compressive strength was conducted on concrete cubes according to BS. EN-12390-3 [66]. Concrete prisms were tested under a three-point loading test according to BS. EN-12390-5 [67] to determine the flexural strength. The splitting-tensile strength and the modulus of elasticity were determined by testing concrete cylinders according to BS. EN-12390-6 [68] and BS EN-12390-13 [69], respectively. Three samples were tested for each property and the average reading was recorded. Compressive and splitting tensile strengths were measured using a 2000 kN hydraulic testing machine. Flexural strength and modulus of elasticity were measured using a 300 kN Universal Testing Machine with a data acquisition system as shown in Fig. 5.

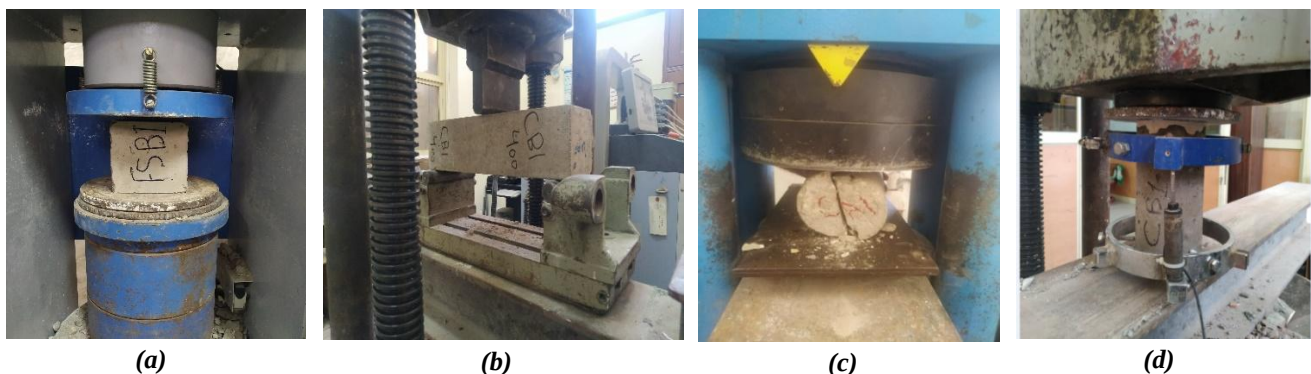


Figure 5 - Mechanical tests setup of GPC and PCC specimens, a) Compressive strength test, b) Flexural strength test, c) Splitting-strength test, d) Modulus of elasticity test

3 Results and discussion

3.1 Mass loss

Mass loss percentages for PCC and GPC cube specimens after exposure to elevated temperatures are shown in Fig. 6. Generally, PCC specimens exhibited higher mass loss than GPC specimens aligning with findings from Sarker et al. [27], Hassan et al. [70] and Razak et al. [71].

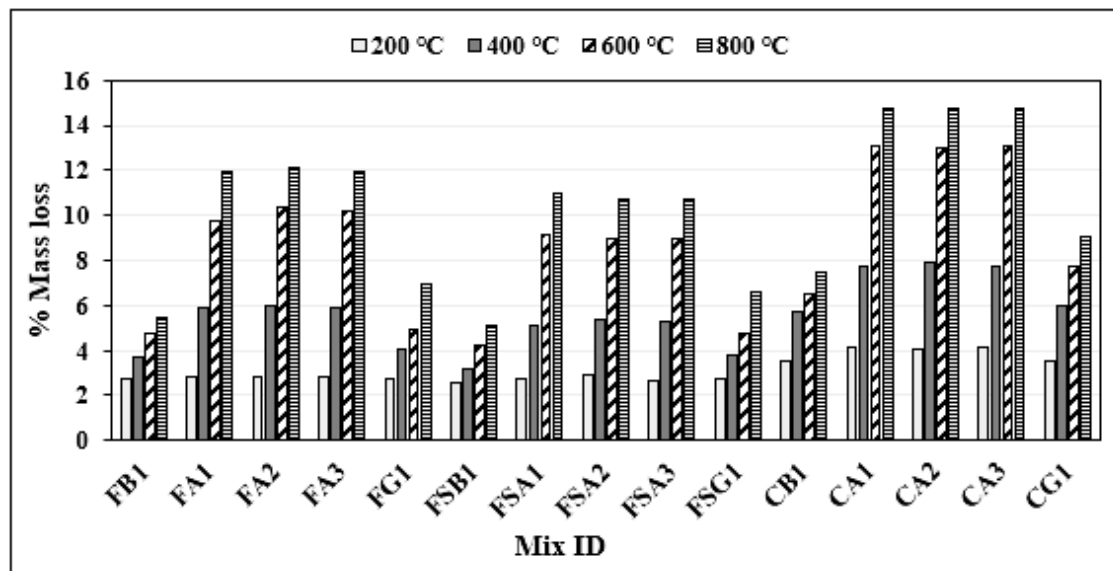


Figure 6 - Mass loss of GPC and PCC mixes

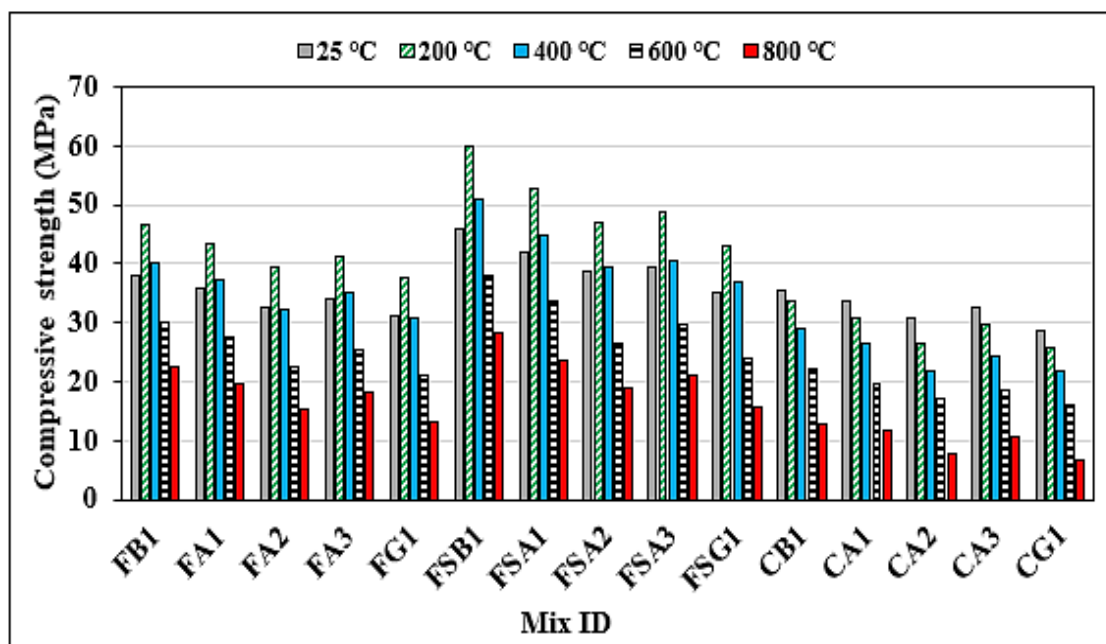
After exposure to 200 °C, GPC specimens, showed mass losses between 2.56% -2.88% whereas PCC specimens losses ranged from 3.51% to 4.17. This mass loss is attributed to free-water evaporation and partial dehydration of geopolymer-gel [72-74]. After exposure to 800°C, mass loss increased significantly due to decomposition of concrete components and was highly affected by the coarse aggregate types. Mass loss of basalt and gravel-based mixes were about (5%-9.1%). On the other hand, crushed dolomite-based mixes exhibited much higher mass loss (10.70%-12.11% for GPC mixes and 15% for PCC mixes). This higher mass loss is attributed to the decomposition of carbonate that exists in dolomite particles in these high temperatures [75].

3.2 Mechanical tests results

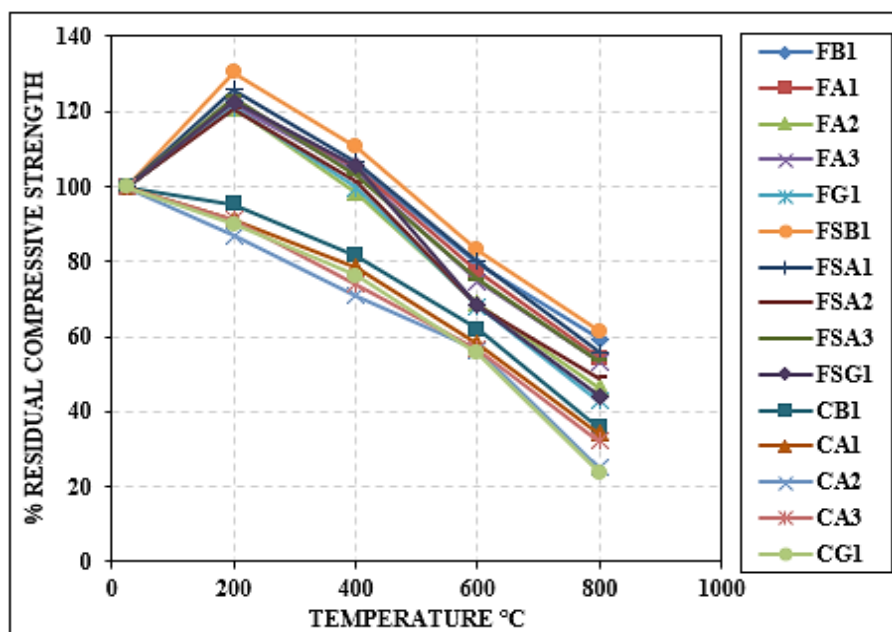
3.2.1 Compressive strength results

The compressive strength results of PCC and GPC mixes before and after exposure to elevated temperatures are summarized in Table 4 and Fig. 7. At ambient temperature, GPC mixes exhibited higher compressive strength than PCC mixes across all aggregate types and sizes. GPC mix achieved the highest compressive strength (45.87 MPa), while PCC mix CG showed the lowest compressive strength (28.58 MPa). Incorporating GGBS increased compressive strength by 13.2–20.7% compared to FA-only GPC, aligning with findings from Ramagiri et al. [46], Lee and Lee [76] and Fang et al. [77]. The improvement in strength is attributed to the additional reaction products resulting in pore refinement and the compactness of the microstructure [78, 79]. Using Basalt aggregates yielded superior compressive strength, compared to using crushed dolomite or gravel, due to enhanced crushing resistance and matrix bonding. The compressive strength of GPC mixes with basalt (FB1, FSB1) outperformed dolomite (FA1, FSA1) and gravel (FG, FSG) mixes by 6.3–9.2% and 22.6–30.7%, respectively. Concrete mixes containing crushed dolomite aggregates A1 with max-size (14 mm) exhibited higher compressive strength than mixes containing either A2 (40 mm), or A3 (20 mm) due to the higher surface area to be bonded with the matrix [80, 81].

Elevated temperature exposure revealed different trends; compressive strength of PCC mixes declined gradually with increasing elevated temperatures up to 800 °C, while compressive strength of GPC mixes increased at 200 °C (21.6% for FA-based, 30.4% for FA/GGBS-based) before decreasing. Aslani and Asif [82] and Zhao et al. [83] found that ambient-cured GPC containing GGBS exhibited higher compressive strength after exposure to 200 °C. Zhang et al. [72] and Hassan et al. [70] also recorded an increase in the compressive strength of ambient-cured FA-based GPC. This initial strength gain in GPC likely results from sintering of unreacted FA particles and enhanced geopolymerization, forming a denser microstructure [83, 84].



(a) Compressive strength values



(b) % Residual compressive strength

Figure 7- Compressive strength and residual compressive strength of GPC and PCC mixes

Table 4 - Test results of compressive strength and flexural strength of different PCC and GPC mixes.

Mix ID	Compressive strength (MPa)					Flexural strength (MPa)				
	25 °C	200 °C	400 °C	600 °C	800 °C	25 °C	200 °C	400 °C	600 °C	800 °C
FB1	38.0	46.5	40.1	30.1	22.9	4.9	5.3	3.6	2.2	1.1
FA1	35.8	43.5	37.4	27.7	19.5	4.6	5.0	3.3	2.0	1.0
FA2	32.7	39.5	32.2	22.5	15.1	4.2	4.41	2.6	1.5	0.5
FA3	33.9	41.3	35.1	25.3	18.0	4.4	4.7	2.9	1.7	0.7
FG	31.0	37.5	30.9	21.1	13.2	3.8	4.0	2.3	1.3	0.2
FSB1	45.9	59.8	50.8	38.1	28.2	5.7	6.4	4.5	2.9	1.6
FSA1	42.0	52.9	44.8	33.6	23.5	5.2	5.5	3.8	2.5	1.3
FSA2	38.8	46.8	39.2	26.5	18.9	4.4	4.7	2.9	1.6	0.6
FSA3	39.5	48.8	40.6	29.6	21.2	4.5	4.7	3.2	1.8	0.9
FSG	35.1	43.0	37.0	24.0	15.5	4.19	4.3	2.8	1.4	0.5
CB1	35.4	33.8	28.9	22.0	12.6	4.71	4.1	3.0	1.8	0.9
CA1	33.8	30.9	26.6	19.7	11.5	4.62	4.0	2.8	1.7	0.6
CA2	30.6	26.6	21.7	17.3	7.6	4.21	3.4	2.3	1.3	0.4
CA3	32.7	29.8	24.2	18.5	10.5	4.37	3.7	2.6	1.5	0.5
CG	28.6	25.7	21.8	15.8	6.8	3.94	3.3	2.3	1.1	0.3

After exposure to 400 °C, GPC retained 98.5%–110.6% of compressive strength. After exposure to 600 °C, the retained compressive strength of GPC mixes was in the range of 68%–83% while it was about 58% for PCC mixes. After exposure to 800 °C, GPC residual strength fell to 42%–61.5%, whereas PCC declined to 23.8%–35.6%. The compressive strength loss in GPC mixes resulted from the loss of chemically bound water and the thermal incompatibility between GP matrix and coarse aggregate [44]. In PCC, dehydration and C-S-H gel decomposition drove the decline [85].

Basalt-based mixes retained higher compressive strength than dolomite or gravel-based mixes after exposure to elevated temperatures. This may be attributed to the lower thermal expansion of basalt aggregate than dolomite and gravel as mentioned in SEM from previous study [71, 86]. Smaller dolomite aggregates (A1) delayed microcrack formation in the interfacial transition zone (ITZ) compared to larger sizes (A2, A3), aligning with findings by [24, 87].

Flexural strength results

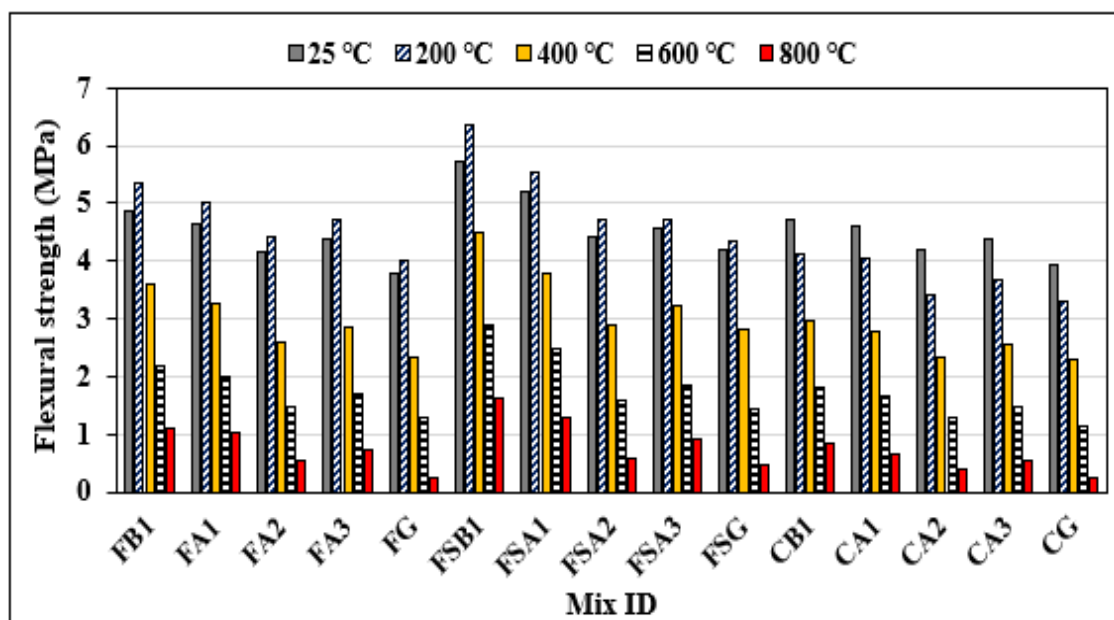
The flexural strength results for PCC and GPC mixes before and after exposure to elevated temperatures are summarized in **Table 4** and **Fig. 8**.

Flexural strength results followed the same trend of the compressive strength results. At ambient temperature, FA/GGBS-based GPC mixes exhibited 3.6%–17.8% higher flexural strength than FA-based GPC and 4.1–22% higher than PCC. Basalt aggregates consistently outperformed crushed dolomite and gravel, while smaller dolomite aggregates A1 (14 mm) showed superior performance over larger sizes A2 (40 mm) and A3 (20 mm).

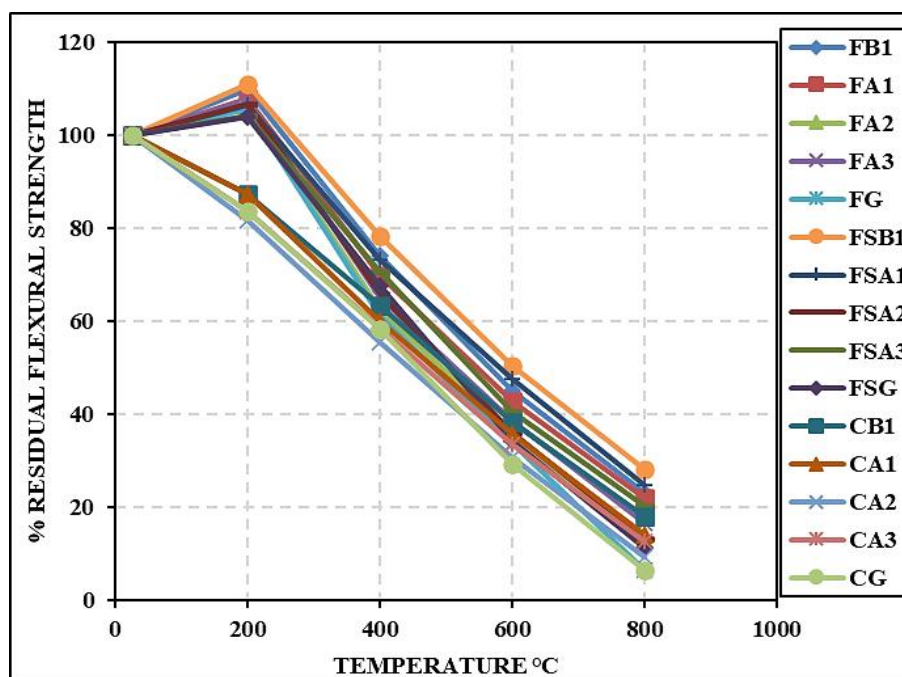
PCC flexural strength declined steadily with rising temperatures (200°C–800°C). In contrast, GPC strength initially increased at 200°C before decreasing at higher temperatures. After exposure to 200°C, flexural strength of FA-based GPC mixes increased by about 5.5%–9.8%, while for FA/GGBS-based GPC mixes increased by about 3.8%–10.9%. Using GGBS with FA led to more enhancement in the flexural strength after exposure to 200 °C than using FA only. PCC mixes exhibited a reduction in flexure strength by about 12.76%–18.54%.

At 400 °C, GPC retained 61.1–78.2% of its initial flexural strength, compared to 55.4–63.3% for PCC. Although GPC mixes exhibited higher residual compressive strength after exposure to 400 °C than the initial strength, they exhibited lower flexural strength after exposure to 400°C. This reduction may be attributed to the development of microcracks.

After exposure to 800 °C, residual flexural strength dropped to 6.5%–23% for FA-based GPC mixes and 11%–28.2% for FA/GGBS-GPC mixes, compared to 6.6%–18% for PCC mixes. The reduction of flexural strength in GPC mixes is attributed to the thermal incompatibility between shrinking GP matrix and expanding coarse aggregates at elevated temperature [45]. Basalt-based mixes retained higher flexural strength than dolomite or gravel-based mixes. Using crushed dolomite A1 (14 mm) was better than using crushed dolomite A2 (40 mm) or crushed dolomite A3 (20 mm). Flexural strength of GPC mix FSA1 was higher than that of GPC mix FSA2 by 118% when exposed to 800 °C.



(a) Flexural strength values



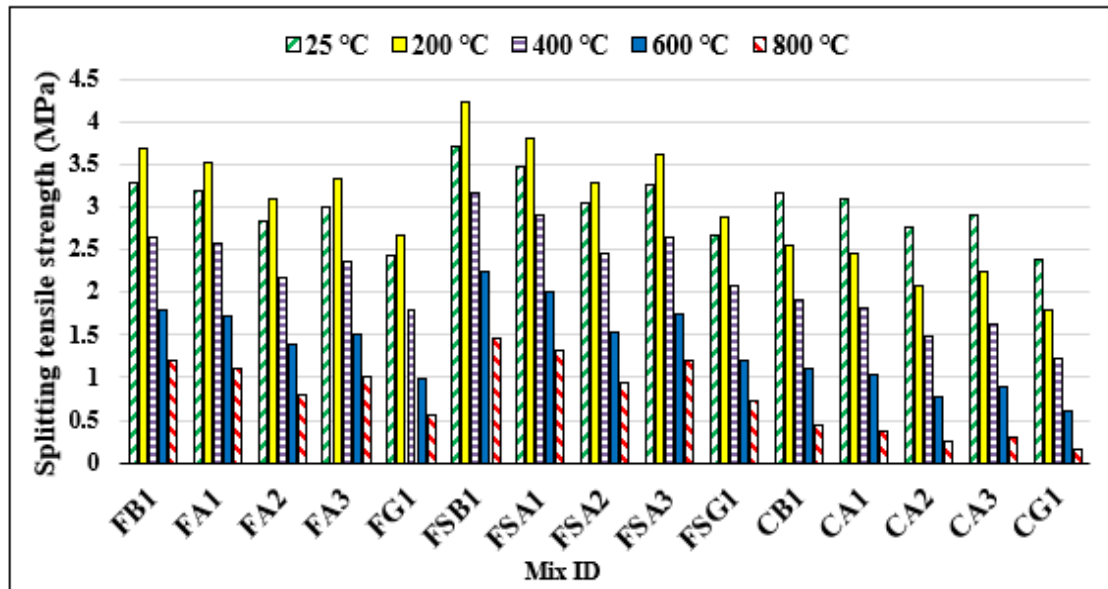
(b) % Residual flexural strength

Figure 8. Flexural strength of GPC and PCC mixes.

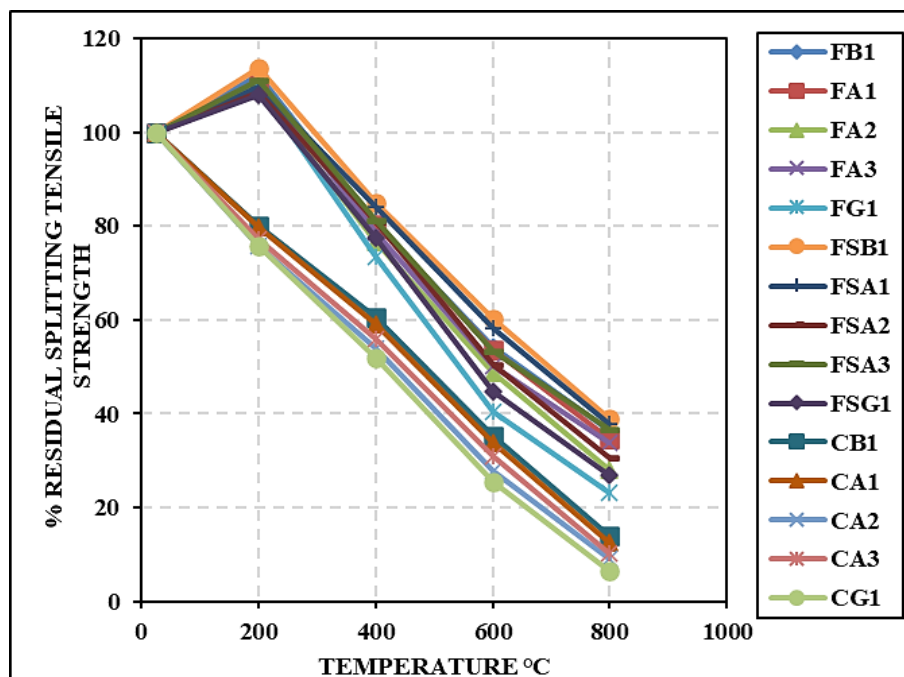
3.2.2 Splitting tensile strength

The splitting tensile strength results for PCC and GPC mixes before and after exposure to elevated temperatures up to 800 °C are summarized in Table 5 and Fig. 9.

FA/GGBS-based GPC mixes exhibited 7%–12.8% higher splitting tensile strength than FA-based GPC and 9.8%–17% higher than PCC. Basalt aggregate demonstrated higher splitting-tensile strength than using crushed dolomite or gravel. Also, using crushed dolomite A1 (14 mm) gave higher splitting-tensile strength than using either crushed dolomite A2 (40 mm) or crushed dolomite A3 (20 mm).



(a) Splitting Tensile strength values



(b) % Residual splitting tensile strength

Figure 9 - Splitting tensile strength of GPC and PCC mixes.

Table 5 - Splitting tensile strength and modulus of elasticity values of different PCC and GPC mixes

Mix ID	Splitting-tensile strength (MPa)					Modulus of elasticity (GPa)				
	25 °C	200 °C	400 °C	600 °C	800 °C	25 °C	200 °C	400 °C	600 °C	800 °C
FB1	3.3	3.7	2.6	1.8	1.2	28.1	29.3	23.1	15.8	10.0
FA1	3.2	3.5	2.6	1.7	1.0	26.8	27.8	22.1	13.8	9.0
FA2	2.8	3.1	2.2	1.4	0.8	23.5	24.0	17.4	10.5	6.0
FA3	3.0	3.3	2.4	1.5	1.0	25.0	25.6	19.5	12.0	5.7
FG	2.4	2.7	1.8	1.0	0.5	21.0	21.5	15.0	8.0	4.2
FSB1	3.7	4.2	3.2	2.2	1.4	30.4	32.3	25.5	17.3	12.0
FSA1	3.5	3.8	2.9	2.0	1.3	28.9	30.5	23.9	15.6	10.5
FSA2	3.0	3.3	2.5	1.5	0.9	25.0	25.7	19.7	11.6	7.1
FSA3	3.3	3.6	2.6	1.7	1.2	26.5	27.1	21.5	13.6	9.0
FSG	2.7	2.9	2.1	1.2	0.7	23.5	24.1	17.5	9.0	5.0
CB1	3.2	2.5	1.9	1.1	0.4	27.5	24.1	17.4	12.3	8.0
CA1	3.1	2.4	1.8	1.0	0.4	25.9	22.2	15.7	11.1	6.6
CA2	2.8	2.1	1.5	0.7	0.2	22.8	19.2	13.3	8.7	4.0
CA3	2.9	2.2	1.6	0.9	0.3	24.2	20.5	14.5	10.0	5.7
CG	2.4	1.8	1.2	0.6	0.1	20.5	17.0	11.5	6.5	3.0

After exposure to 200 °C, FA-based GPC showed a 9.1%–12.2% increase in splitting tensile strength, while FA/GGBS-based GPC exhibited an 8%–13.7% enhancement. In contrast, PCC retained only 75.7%–80% of its initial strength. After exposure to 400 °C, microcrack development caused reductions in all mixes, GPC mixes retained 40.3%–60.3% of its strength compared to 25.5%–35.1% for PCC. After exposure to 800 °C, residual splitting tensile strength declined sharply: FA-based GPC mixes retained 23%–36.3%, FA/GGBS-based GPC mixes retained 26.9%–39%, and PCC mixes retained only 6.4%–14%. The superior performance of FA/GGBS-based GPC highlights the role of GGBS in enhancing geopolymerization and thermal stability.

Taking into consideration the coarse aggregates type, using basalt aggregate gave higher residual splitting-tensile strength than crushed dolomite or gravel. On the other hand, using gravel as coarse aggregate gave the least values of splitting-tensile strength especially after exposure to 600 °C and 800 °C due to the higher thermal incompatibility between paste and gravel. The size of crushed dolomite aggregates has a clear effect on the splitting-tensile strength of concrete mixes when exposed to elevated temperatures. Using dolomite A1 (14 mm) was better than using crushed dolomite A2 (40 mm) or crushed dolomite A3 (20 mm).

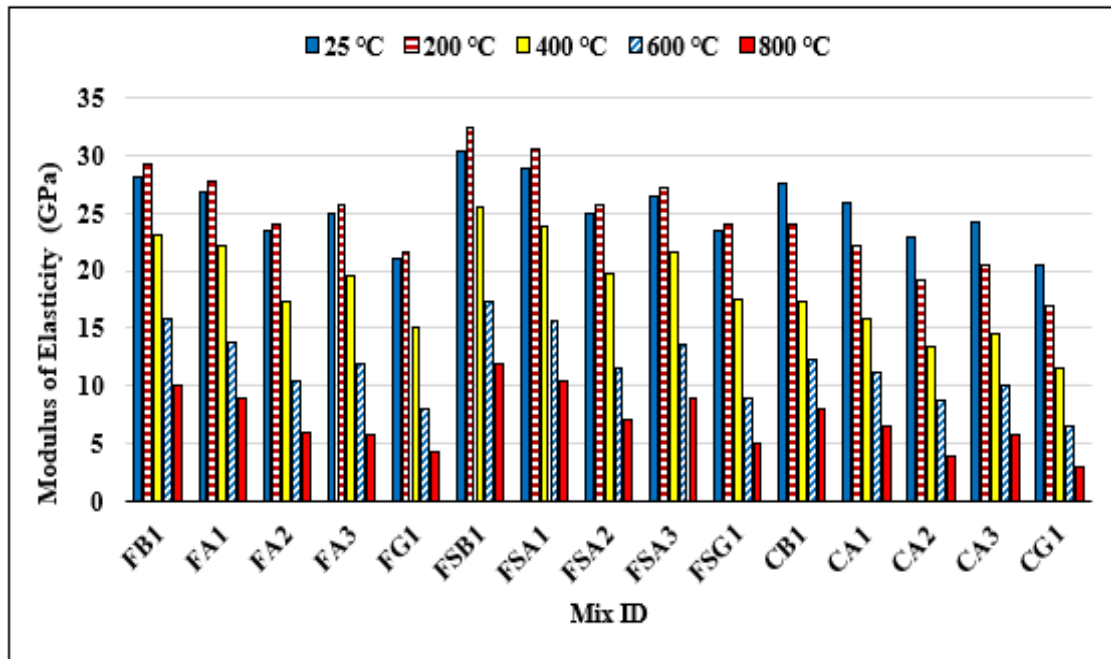
3.2.3 Modulus of elasticity

The results of modulus of elasticity for different PCC and GPC mixes before and after exposure to elevated temperatures up to 800 °C are summarized in Table 5 and Fig. 10.

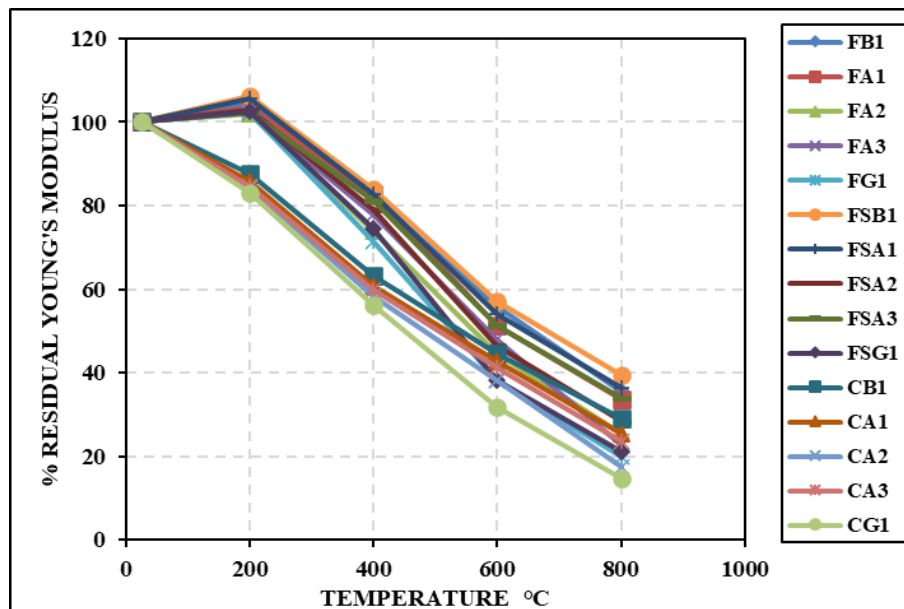
At ambient temperature, FA/GGBS-based GPC mixes exhibited 6%–14.6% higher modulus values than PCC mixes, while FA-based GPC showed a 2.2%–3.1% advantage than PCC mixes. Using GGBS in GPC mixes enhanced the modulus of elasticity by 6%–11.9% compared to FA-based GPC mixes. Basalt aggregate provided the highest stiffness, followed by crushed dolomite (A1: 14 mm). Modulus of elasticity of concrete mixes FSA1, FA1 and CA1 was higher than that of mixes FSA2, FA2, and CA2 by 14.04%, 15.6% and 13.6%, respectively.

At 200 °C, FA-based GPC modulus and FA/GGBS-based GPC modulus increased marginally (2.1%–46.3%) and (2.3%–6.25%, respectively) whereas PCC retained 82.9–87.6% of its initial stiffness. After exposure to 400 °C and 600 °C, all GPC and PCC mixes exhibited a reduction in modulus of elasticity due to the development of microcracks [45]. After exposure to 800 °C, residual modulus values declined: FA/GGBS-based GPC retained 21%–39.5%, FA-based GPC retained 20%–35.6%,

and PCC retained only 14.6%–29.1%. The superior thermal resilience of GPC, particularly FA/GGBS blends, stems from the stable geopolymer matrix and reduced thermal incompatibility with basalt aggregates. Smaller dolomite aggregates (A1) delayed ITZ degradation, aligning with trends observed in compressive and flexural strengths [24].



(a) Modulus of elasticity values



(b) %Residual modulus of elasticity

Figure 10 - Modulus of elasticity of GPC and PCC mixes

4 Prediction of residual compressive strength for GPC using Artificial Neural Network models

Two different data sets have been used in this study. Data set 1 was used to build ANN model (ANN-1) to predict compressive strength of ambient-cured GPC after exposure to elevated temperatures. The input parameters and compressive strength were collected from various prior investigations [46, 70, 72, 82, 88]. In addition, GPC mixes from the test results of

the current experimental work were used in data set 1. Data set 2 was used to build ANN model (ANN-2) to predict compressive strength of heat-cured GPC after exposure to elevated temperatures. Input parameters and compressive strength were collected from different previous studies [24, 27, 28, 30, 44, 65, 70, 72, 89].

4.1 Structure of Model ANN-1 for ambient cured GPC mixes

The different parameters (inputs) used in model ANN-1 were FA content, GGBS content, molarity of hydroxide solution, solution to binder ratio, extra water to binder ratio, thermal expansion of coarse aggregate, nominal maximum size of coarse aggregate, fire temperature and fire rate as inputs. The output of model ANN-1 is the residual compressive strength of GPC mixes after exposure to different elevated temperatures.

4.2 Structure of Model ANN-2 for heat cured GPC mixes

The different parameters (inputs) used in model ANN-2 were FA content, GGBS content, molarity of hydroxide solution, solution to binder ratio, extra water to binder ratio, thermal expansion of coarse aggregate, nominal maximum size of coarse aggregate, curing temperature, fire temperature, fire rate and fire duration as inputs. The output of model ANN-2 is the residual compressive strength of GPC mixes after exposure to different elevated temperatures.

4.3 Training and testing of ANN models

The computer program was performed under MATLAB R2013a software using the neural network toolbox. In the training process, data set-1 and data set-2 were used to learn the ANNs models ANN-1 and ANN-2, respectively using the Levenberg – Marquardt backpropagation algorithm. Both ANN models included one output layer, input layer, one hidden layer and the in-between connections. The numbers of the neuron on the hidden layer as well as the percentage of data in training, validation and testing were changed to find best results and accuracy. Several performance metrics were used in this study to evaluate model performance such as adjusted R², root mean square error (RMSE) difference and the normalized root mean square error (NRMSE). The equation of the root mean square error has been adopted to measure the accuracy between the actual and predicted values using Eq. 1 [49, 57].

$$RMSE = \sqrt{\frac{1}{N} \sum_{n=1}^N -(A_n - P_n)^2} \quad (1)$$

where A_n is the actual value, P_n is the predicted value and N is the number of data points in the training data set.

Normalizing the RMSE facilitates the comparison between data sets or models with different scales and is calculated using Eq. 2 [49, 57].

$$NRMSE = \frac{RMSE}{S} \quad (2)$$

where S represents the mean of the actual values.

The R^2 has been also estimated for each ingredient using Eq. 3 [49, 57].

$$R^2 = \frac{\sum (A_n - P_n)^2}{(A_n - S)^2} \quad (3)$$

When R^2 nears to one it is a sign of good or more accuracy, and on the other hand when it nears to zero it is a sign of bad or less accuracy [49]. Several trials were run by changing number of neurons, then the predicted value of compressive strength were calculated. The actual and predicted values of compressive strength were then plotted on graphs. In the plotted graph, three lines including line of perfect values as well as two lines shifted by $\pm 20\%$ from the perfect one were drawn [49, 57].

4.4 Results and discussion of ANN models

For Model ANN-1, the best results were obtained from taking 75%-10%-15% of data in training, validation and testing with 5 neurons as shown in Fig. 11-a. The values of R^2 , RMSE and NRMSE were 0.940, 3.58 and 0.111, respectively, which indicates high accuracy of model ANN-1.

For model ANN-2, the best results were obtained from taking 60%-30%-10% of data in training, validation and testing with 5 neurons as shown in Fig. 11-b. The values of R^2 , RMSE and NRMSE were 0.887, 6.31 and 0.155, respectively, which indicates high accuracy of model ANN-2.

To show the performance of the ANN models, the actual values of compressive strength after exposure to elevated temperatures (from data set-1 and data set-2) versus the predicted values from model ANN-1 and model ANN-2 are plotted in Figs. 12-a and 12-b, respectively. From Fig. 12 it is obvious that most of the points lie between the two boundary lines 80% and 120% (about 95.8% for model ANN-1 and 87% for model ANN-2).

To rigorously evaluate the generalization performance of ANN models, a 5-fold cross-validation procedure was employed. This approach balances computational efficiency with reliable performance estimation by partitioning the dataset into five equal subsets. For each iteration, four folds were used for training, and the remaining fold served as the validation set. This process was repeated until all folds had been utilized once for validation, ensuring every data point contributed to both training and testing phases. Across the five folds, the average R^2 value for model ANN-1 and ANN-2 were 0.7 and 0.61, respectively (with standard deviation values of 0.23 and 0.12). This indicates moderate explanatory power, suggesting that the ANN captures a meaningful portion of the underlying data patterns while highlighting opportunities for refinement.

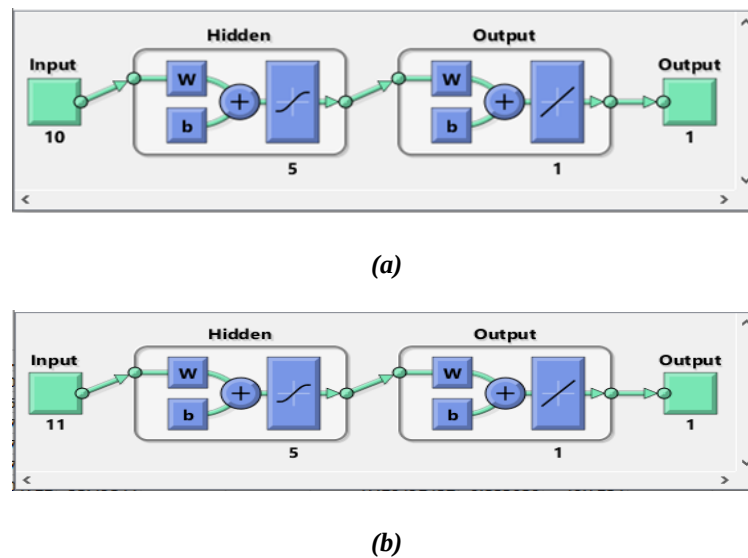
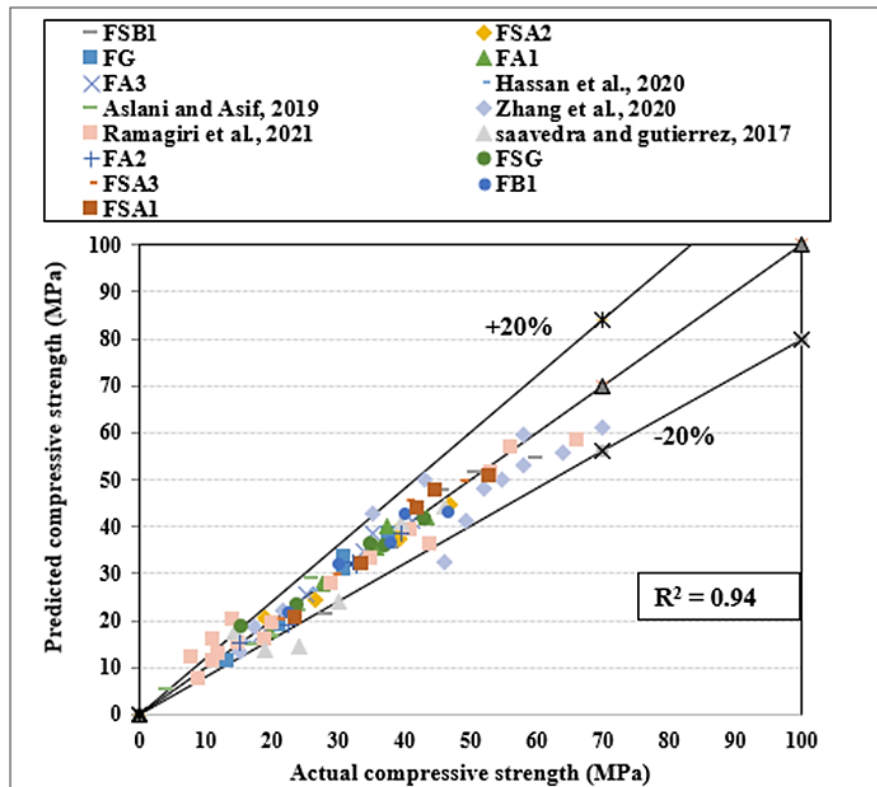


Figure 11 - Neural network of a) model ANN-1 and b) model ANN-2

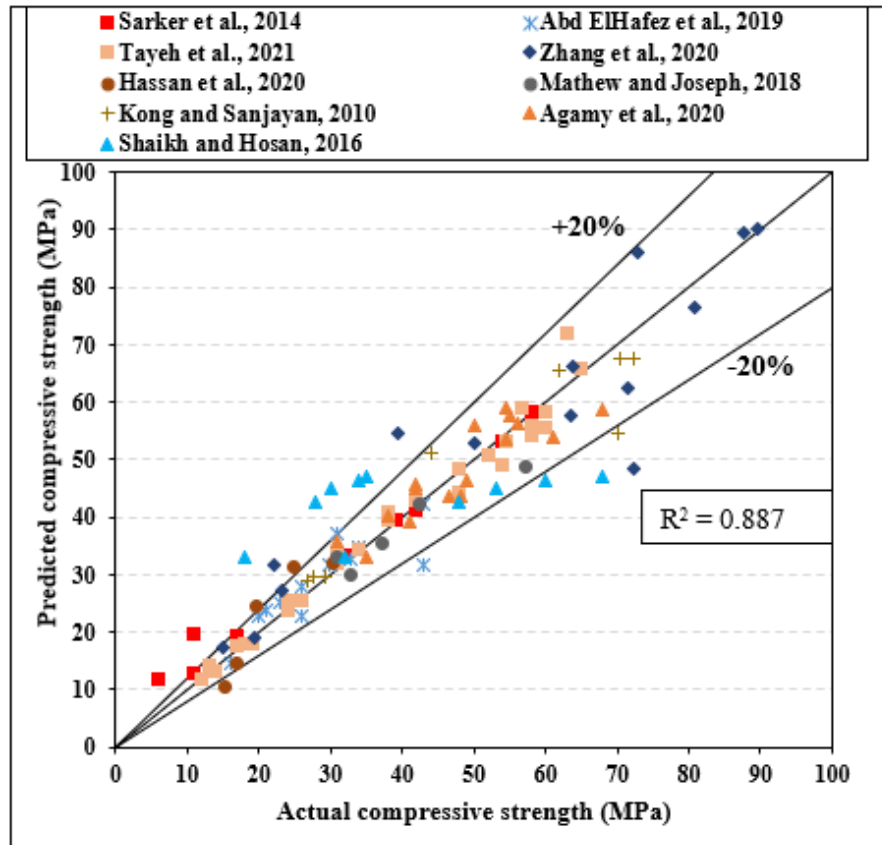
5 Cost/Scalability of GPC

The practical adoption of GPC depends on balancing material economics with scalability. While the main binders for GPC, (FA) and (GGBS) [19], are industrial by-products (from coal power plants and steel mills), their cost-effectiveness relies substantially on regional availability. In areas with several coal or steel industries, these materials are low-cost and abundant. However, in regions lacking such infrastructure, transportation and logistics costs can inflate expenses, posing challenges for large-scale applications [90]. Moreover, alkaline activators like sodium silicate (Na_2SiO_3) and potassium hydroxide (KOH) remain a cost constraint. For example, Na_2SiO_3 production involves energy-intensive silica smelting, while KOH requires electrolysis of potassium chloride.

Scalability also depends on handling alkaline solutions safely. Unlike PC, which uses water as the primary solution, GPC requires careful storage and mixing of corrosive alkaline liquids—a hurdle for conventional concrete batching plants [91]. Yet, ambient-cured GPC eliminates the need for energy-intensive heat curing (60–90°C), slashing energy use by ~50% compared to heat-cured geopolymers [92]. This makes it more practical for on-site applications, especially where FA/GGBS blends are locally accessible. Future advancements, such as recycling spent alkaline solutions or developing bio-based activators (e.g., rice husk ash-derived silicates), could further lower costs. For now, GPC's scalability shines in fields prioritizing low-carbon goals over short-term economics, such as infrastructure projects near industrial hubs with abundant FA/GGBS stockpiles.



(a) ANN model ANN-1 (ambient cured GPC mixes)



(b) ANN model ANN-2 (heat cured GPC mixes)

Figure 12 - Actual values versus predicted values for the two ANN models

6 Influence on design codes, material selection, or fire safety strategies in construction

Our results can contribute to the development of specific fire resistance guidelines for GPC structures, as current building codes primarily focus on traditional PCC [93]. The superior performance GPC under high temperatures, as demonstrated in our study, suggests the need for distinct fire resistance ratings and specifications [91].

The study's results can inform the development of specific guidelines for aggregate selection in fire-resistant GPC. This is crucial as the chemical composition and size of aggregates significantly influence the concrete's post-fire performance. Also, the results emphasize the importance of establishing rigorous quality control measures for raw materials, especially considering the variability in industrial by-products used in GPC [94]. Using machine learning programs to find the optimum mix design of fire-resistant GPC is a need.

The findings support the integration of environmentally friendly fire-resistant materials in construction, as GPC offers both superior fire resistance and reduced carbon footprint compared to PCC [95]. The demonstrated performance of GPC under high temperatures supports its use in critical infrastructure where fire resistance is paramount. This can influence the selection of materials for fire-prone areas or structures requiring enhanced fire protection.

7 Conclusions

In this study, the effect of elevated temperatures on the mechanical properties of ambient-cured geopolymer concrete (GPC) mixes were investigated. Different GPC mixes (FA-based GPC and FA/GGBS-based GPC) as well as Portland cement concrete mixes (PCC) were exposed to elevated temperature 200 °C, 400 °C, 600 °C, and 800 °C. The effect of different coarse aggregate types and sizes were studied. Furthermore, artificial neural networks (ANN) models were presented to predict the residual compressive strength of ambient and heat cured GPC after exposure to elevated temperatures. The key findings include:

- Ambient-cured GPC mixes exhibited higher compressive, flexural, splitting-tensile strengths and modulus of elasticity than PCC by 16%, 5%, 8% and 7%, respectively at ambient conditions. Moreover, GPC mixes showed better performance than PCC mixes after exposure to elevated temperatures.
- Incorporating 25% GGBS in GPC mixes enhanced the mechanical properties either at ambient conditions or after exposure to elevated temperatures. Compressive, improved by about (15%-21%) at ambient condition when compared to FA-based GPC. Residual compressive strength of FA/GGBS based GPC and FA-based GPC after exposure to 800°C were (44.2%-66.5%) and (42%-60%), respectively.
- Coarse aggregate types and sizes significantly impacted the mechanical properties of both PCC and GPC mixes especially after exposure to elevated temperatures.
- Using basalt aggregate provided the highest residual mechanical properties outperforming gravel and crushed dolomite. Thermal incompatibility between gravel and paste and decomposition of crushed dolomite at high temperatures caused more reductions in mechanical properties.
- GPC or PCC contained smaller crushed dolomite (14 mm) exhibited better residual mechanical properties compared to those larger sizes (20 mm and 40 mm) after exposure to 800°C due to the delayed interfacial transition zone (ITZ) microcracking.
- This study demonstrated the feasibility of using artificial neural networks (ANN) in predicting residual compressive strength after exposure to elevated temperatures for either heat-cured ($R^2=0.887$) or ambient-cured ($R^2=0.94$) GPC mixes.
- Further studies including Scanning Electron Microscopy (SEM) are essential for elucidating the microstructural evolution of GPC subjected to elevated temperatures, particularly in understanding crack propagation mechanisms and the degradation of the aggregate–matrix interface.
- Further studies applying advanced statistical methods and data-driven strategies, such as advanced machine learning (ML) models, to quantify variability and strengthen predictive reliability are essential.

These findings highlight the potential benefits of GGBS incorporation, the influence of aggregate types and sizes, and the effectiveness of ANN models in understanding and predicting the behavior of GPC under varying temperature conditions.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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