Mechanical Performance of Sustainable Geopolymer Lightweight Concrete Exposed to Fire

Faisal Sadeq Abdulkareem
Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
faissal.abd2301@coeng.uobaghdad.edu.iq (corresponding author)

Nada Mahdi Fawzi Aljalawi
Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
nada.aljalawi@coeng.uobaghdad.edu.iq

Received: 2 June 2025 | Revised: 24 June 2025 | Accepted: 7 July 2025

DOI: https://doi.org/10.48084/etasr.12528

ABSTRACT

The need for sustainability and reduced CO_2 emissions is leading to increased use of industrial waste and byproducts from the building industry. Geopolymer concrete, is an environmentally sustainable alternative to conventional Portland cement binders and preserves the natural resources. This study presents the mechanical properties of specimens subjected to fire, with the samples being exposed to fire at temperatures of 400 °C, 600 °C, and 800 °C for 1 h in a period of 56 days. The results reveal a drop in the mechanical properties as the temperature increases, with the most significant deterioration taking place at 800 °C. The greatest reduction in compressive, splitting tensile, and flexural strength was observed in the unreinforced control mix at higher temperatures, while the specimens reinforced with 1% basalt fiber showed minimal strength degradation, indicating enhanced fire resistance and structural integrity under thermal conditions.

Keywords-geopolymer lightweight concrete; compressive strength; splitting tensile strength; flexural strength; basalt fiber; fire flame

I. INTRODUCTION

The usage of sustainable materials is highly valued in the building and housing industries, leading to the development of new concrete. Due to their pozzolanic properties, industrial byproducts, such as Fly Ash (FA) and blast furnace slag, municipal waste materials, such as glass and ceramic powder, and agricultural residues, such as palm oil fuel ash, have been used as alternatives to Ordinary Portland Cement (OPC) [1]. Ground Granulated Blast Furnace Slag (GGBFS) and FA improve the concrete performance while promoting economic and environmentally friendly practices [2, 3]. Compared to OPC, the geopolymer technology can reduce the CO_2 emissions and exhibits superior thermal endurance in high-temperature environments [4]. Geopolymers are innovative construction materials that can substitute traditional OPC. Geopolymer concrete binder components include FA, powdered granulated blast furnace slag, and metakaolin, which are aluminosilicate compounds. The dominant alkaline activator for geopolymer concrete formulations is a liquid mixture of sodium or potassium hydroxide and sodium or potassium silicate [5]. Integrating fiber into concrete can significantly improve its crack resistance, flexural and tensile strength, while enhancing its toughness and ductility [6]. Geopolymer composites provide high early compressive strength, minimal water absorption, and thermal resistance, which facilitates the expedited construction and decreases labor [7]. Basalt fiber exhibits high working temperatures and excellent resistance to impact loads, fire, and chemical corrosion.

Compared to normal concrete, the benefits of lightweight concrete include decreased structural dead weight, enhanced thermal insulation, and reduced transportation costs [8]. Using lightweight aggregates is a common technique for making lightweight construction materials. Lightweight Aggregate Concrete (LWAC) has a high strength-to-weight ratio, excellent tensile strength, a low coefficient of thermal expansion, and superior thermal and acoustic insulation properties due to the air gaps in its structure [9]. Concrete offers superior fire resistance compared to the steel structures and non-combustible materials, which fracture and spall and have poor thermal conductivity and mechanical qualities. This is one of the factors that makes concrete so appealing and yields concerns [10]. Geopolymers are more fire-resistant than OPC, due to their microstructure and pore structure. However, geopolymerization materials do not contain water. In contrast, hydrated cement needs water, and Calcium Silicate Hydrate

(CSH) breaks down at high temperatures, decreasing the mechanical strength [11]. Strength degradation after heat exposure at 800 °C decreases with an increase in the NaOH concentration, especially from 10 M to 16 M [12]. Geopolymer concrete exhibits better fire resistance than OPC concrete due to less cracking, no spalling up to 1000 °C, and greater retained strength [13]. Concrete exposed to fire loses strength, especially when cooled suddenly [14, 15]. Microstructural densification was observed by Scanning Electron Microscopy (SEM) analysis; the thermal mismatch between the matrix and aggregates mostly causes strength loss. Authors in [16], show that lightweight, geopolymer-based FA provides great fire resistance despite its lower density and lower compressive strength compared to unfoamed FA when subjected to temperatures between 200 °C and 800 °C. Authors in [17], discovered that the maximum cracking width increased as the fire temperature increased. The goal of this research is to reduce the CO_2 emissions in the cement production industry while generating high-quality, strong concrete. The impact of flame exposure at various temperatures (400 °C, 600 °C, 800 °C) on the mechanical properties of basalt fiber-reinforced geopolymer lightweight concrete with different ratios was examined and the compressive, tensile, and flexural strengths after 56 days of curing were determined and compared before and after fire exposure. Previous studies have reported that increasing the perlite lightweight aggregate decreases mechanical properties, such as compressive, tensile, and flexural strength; however, the gradual cooling after fire exposure helps retain higher residual strength values [18].

II. MATERIALS

The materials used in this study are presented in Figure 1.

Fig. 1. Materials used in this study.

A. *Fly Ash*

The composition properties of the FA utilized in this study classify it as Type F and meet the ASTM C618, 2023 criteria [19], as shown in Table I.

TABLE I. CHEMICAL COMPOSITION ANALYSIS OF FA AND ITS CONFORMITY WITH ASTM C618

Oxides	**Contents %**	**Requirements according to ASTM C618 Type F**
SiO2	46.65	≥ 50
Al2O3	25.09	
Fe2O3	5.47	
SO3	0.16	Max. 5%
MgO	0.8	-
CaO	1.85	Max. 18%
L.O. I	0.47	Max. 6%

B. *Slag*

The chemical composition of GGBFS indicates that it is a suitable material for use in this study, as it meets the requirements of ASTM C989 [20], as depicted in Table II.

TABLE II. CHEMICAL COMPOSITION ANALYSIS OF GGBS AND ITS CONFORMITY WITH ASTM C989

Oxides	**Contents %**		**Requirements according to ASTM C989**
SiO_2	26.38		-
Al_2O_3	13.88		-
Fe_2O_3	0.56		-
S	0.184		Max. 2.5%
NaOH	0.442	NaOH + 0.658 K_2O = 0.809	(0.6 – 0.9)
K_2O	0.558		
MgO	6.61		-
CaO	35.58		-
L.O. I	0.37		-

C. *Sodium Hydroxide NaOH*

Caustic soda flakes with a purity level of 99% were then mixed with distilled water to create a NaOH solution. The NaOH solution met the ASTM E291-2009 [21] requirements, and the molar concentration of the used NaOH was 12 mol/L.

D. *Sodium Silicate Na_2SiO_3*

The composition of sodium silicate solutions is determined by the molar ratio of Na_2O to SiO_2, which influences the silicate polymerization, and the concentration is dependent on the H_2O content.

E. *Water*

The dissolution of the NaOH flake in distilled water is necessary to produce the NaOH solution. However, Saturated Surface Dry (SSD) water was used in the aggregate's production, in accordance with IQS 1703-2018 [22].

F. *Pumice*

Pumice, a lightweight volcanic rock, was imported from Turkey and was used as coarse aggregate in this research study. The nominal size ranges from 12.5 mm to 4.75 mm. Tables III and IV present the chemical analysis component and gradation of lightweight pumice aggregates, respectively, in accordance with ASTM C330 [23].

TABLE III. CHEMICAL ANALYSIS OF LIGHTWEIGHT PUMICE AGGREGATES

Oxide	Concentration %
SiO_2	49.6
Al_2O_3	16.2
Fe_2O_3	3
SO_3	0.07
CaO	7.08
MgO	3.1
L. O. I	4.39

G. Fine Aggregate

Sand was used as the fine aggregate in this experiment, and as shown in Table V, it was classified as zone four and determined in accordance with the specifications stipulated in IQS (No. 45/1984) [24].

TABLE IV. PUMICE GRADATION ACCORDING TO ASTM C330-17

Sieve size (mm)	Accumulative passing wt. %	Limit according to ASTM C330-2017
19	100	100
12.5	100	90 – 100
9.5	55	40 – 80
4.75	0	0 – 20
2.36	0	0 – 10
0.075	0	0 – 10

TABLE V. SIEVE ANALYSIS AND COMPOUND CONTENT OF NATURAL FINE AGGREGATES

Sieve size mm	Cumulative passing %	Limit of IQS No.45/1984 Zone 4
10	100	100
4.75	100	95-100
2.36	100	95-100
1.18	100	90-100
0.6	90	80-100
0.3	30	15-50
0.15	5	0-15

H. Superplasticizer

A high-range water-reducing admixture, Hard-Con-22-TS, from Hard Stone Company, was used in the study. The basis for this superplasticizer is polycarboxylate ether, which complies with the ASTM C494 Standard Type A and G [25].

I. Basalt Fiber

Basalt fiber chopped strands measuring 12 mm in length and 0.13 µm in diameter were used, resulting in an aspect ratio of 92.3.

III. MANUFACTURE OF GEOPOLYMER LIGHTWEIGHT CONCRETE

A. Mixing

- The process of mixing is important in the production of geopolymer lightweight concrete. The present study used the lightweight geopolymer concrete mixing method [26] with an electrical mixer (0.01 m³).
- Subsequent to the sifting process, the dust and debris were extracted from the pumice and fine aggregates.
- The mixing procedure was initiated as follows: the lightweight aggregate, consisted of pumice, and the fine aggregate, consisted of sand, were combined for 1 min in the mixer. Subsequently, a quarter of the solution was added and the mixture agitated for an additional min. FA and GGBS were added to the pumice and sand after the mixer was stopped, and the mixture was then left for 1 min. The superplasticizer was initially added in a proportion of three-quarters of the total mixture, in accordance with the specified dose. This was done in a gradual manner, over the course of 3 min, while the mixer was rotating. Following the mixing process, the geopolymer concrete was ready for mold casting. The selection of the geopolymer lightweight concrete mixture led to the examination of varying basalt fiber percentages (0.5, 0.75, and 1) by volume. This study aimed to ascertain the impact of these variables on the composite's mechanical properties prior to and following the combustion process. Table VI presents the composite design of geopolymer lightweight concrete, characterized by a molarity of 12 and a ratio of SH: SS of 1:2.5.

TABLE VI. MIX PROPORTION FOR GEOPOLYMER LIGHTWEIGHT CONCRETE, WEIGHT IN KG/M^3

Mix	FA	GGBS	Pumice	Sand	A/B	SP%	Basalt fiber
GLRef.	162	378	530	450	0.45	1.5	-
GLBF 0.5%	162	378	530	450	0.45	1.5	13.5
GLBF 0.75%	162	378	530	450	0.45	1.5	20.25
GLBF 1%	162	378	530	450	0.45	1.5	27

B. Curing

The concrete specimens were subjected to a curing process in a laboratory oven set at 80°C for 24 h, as shown in Figure 2. The specimens were transferred to an alternate oven for cooling and temperature maintenance, ensuring that the temperature remains consistent until the designated test date [27].

Fig. 2. Placing the sample into laboratory oven.

IV. TEST METHODS

A. Fire Flame

The experiment evaluated the fire resistance of various geometric shapes, including cubes, cylinders, and prisms, by applying direct flames at temperatures of 400 °C, 600 °C, and 800 °C for 60 min, as displayed in Figure 3. Then the specimens were tested for compressive and splitting tensile strength, as well as flexural strength. The process was designed in accordance with the principles of thermal exposure delineated in ASTM E119. After 56 days, the specimens were exposed to flames from a controlled gas hob. Thermocouples were used to monitor the surface temperatures on every specimen. Subsequent to the exposure, each specimen was permitted to undergo a cooling period of 24 h under standard conditions prior to the execution of mechanical testing [28].

B. *Compressive Strength*

The compressive strength of the specimens was measured in accordance with the standards outlined in BS-EN-12390-3, 2019 [29], and were examined for a period of 56 days. The mean compressive strength of three specimens was measured for each test:

$$fc = P / A \tag{1}$$

where f_c is the compressive strength in MPa, P is the maximum applied load in N, and A is the cross-section area in mm^2.

Fig. 3. Fire flame setup used for testing.

C. *Splitting Tensile Strength*

The tensile strength testing was carried out in accordance with the standards outlined in ASTM C496-17 [30]. Cylinders measuring 100 mm × 200 mm were used and examined after 7 and 28 days. The mean value of three cylinders was calculated as:

$$f_t = (2 \times P) / (\pi \times l \times d) \tag{2}$$

where f_t is the splitting tensile strength in MPa, P is the applied load in N, l is the length of cylinder in mm, and d is the diameter of cylinder in mm.

D. *Flexural Strength*

In order to calculate the flexural strength, the geopolymer lightweight concrete was subjected to a center point load test in accordance with ASTM C293M-16 [31] after 7 and 28 days using the average of three prism specimens (75 × 75 × 380 mm):

$$f_r = (3 \times P \times L) / (2 \times b \times d^2) \tag{3}$$

where f_r is the flexural strength in MPa, L is the length in mm, P is the maximum load in N, b is the width in mm, and d is the depth in mm.

V. RESULTS AND DISCUSSION

The concrete specimens were subjected to a flame test using a natural gas fire apparatus to simulate a real fire scenario. The samples were exposed to temperatures of 400 °C, 600 °C, and 800 °C for 60 min. The objective of the tests was to evaluate the concrete sample's residual strength following the exposure to fire.

A. *Compressive Strength*

A significant characteristic of hardened concrete is its compressive strength, as illustrated in Table VII and Figure 4.

TABLE VII. RESULTS OF COMPRESSIVE STRENGTH EXPOSED TO DIFFERENT FIRE FLAMES

Mix	Before burning	400 °C	600 °C	800 °C
GLRef.	31.5	30	21.4	17
GLBF0.5%	34.5	33.5	25.9	18
GLBF0.75%	35.7	34.8	27.5	18.9
GLBF1%	36.2	35.8	29.3	19.6

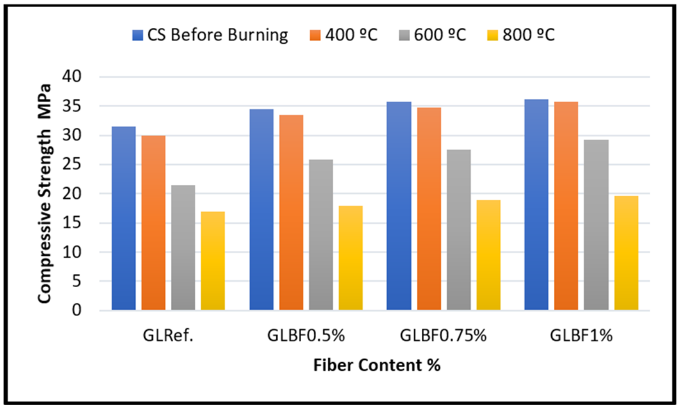

Fig. 4. Compressive strength of geopolymer lightweight concrete with different basalt fiber contents exposed to different fire flame temperatures.

The results of the compressive strength analysis were obtained before and after the exposure to fire flames. The samples that were reinforced with varying proportions of basalt fibers (0.5%, 0.75%, and 1%) exhibited a substantial increase in strength compared to the GLRef specimens. This can be attributed to the role of the fibers as a bridging agent, which restricts or postpones the formation of cracks [32]. According to the experimental results, the compressive strength of the unreinforced geopolymer lightweight concrete diminished by 4.76%, following the exposure to a 400 °C fire flame. The specimens reinforced with 0.5%, 0.75%, and 1% basalt fiber exhibited a decrease of 2.9%, 2.52%, and 1.1%, respectively, at the same temperature. At a temperature of 600°C, the compressive strength exhibited a notable decrease, with drops of 32%, 24.9%, 23%, and 19.1% for the reference sample, and 0.5%, 0.75%, and 1% for the basalt fiber-reinforced samples, respectively. The extended exposure to 800 °C resulted in the most significant degradation, with strength reductions of 46%, 47.8%, 47.1%, and 45.9%, respectively. The elevated fiber content demonstrated a marginal mitigating effect at 400 °C; nevertheless, higher temperatures (600 °C, 800 °C), resulted in increasing degradation highlighting the constraints of basalt fiber reinforcement under extreme thermal conditions [33].

B. Splitting Tensile Strength

As presented in Table VIII and Figure 5, the outcomes of the splitting tensile strength test show the enhancement resulting from the fiber usage, leading to a substantial increase in strength and stiffness. This phenomenon leads to a reduction in deformation and potentially affects or delays the underlying mechanisms of composite failure. According to the experimental findings, the splitting tensile strength of the unreinforced geopolymer lightweight concrete decreased by 5.8%, following the exposure to a 400 °C fire flame. The specimens reinforced with 0.5%, 0.75%, and 1% basalt fiber exhibited a decrease of 3.15%, 3.34%, and 3.36%, respectively. At a temperature of 600 °C, the compressive strength exhibited a notable decrease, with drops of 36%, 32.4%, 29.9%, and 25.4% for the reference specimen, and 0.5%, 0.75%, and 1% for the basalt fiber-reinforced samples, respectively. The exposure to 800 °C for an extend period resulted in the most substantial degradation, with strength reductions of 60.5%, 48.5%, 44.4%, and 40.7% for the respective mixes [34]. The increased fiber content presented a modest mitigating effect at 400 °C; nevertheless, the elevated temperatures (600°C and 800°C) led to a progressive increase in degradation, underscoring the constraints of basalt fiber reinforcement under extreme thermal conditions.

TABLE VIII. RESULTS OF SPLITTING TENSILE STRENGTH EXPOSED TO DIFFERENT FIRE FLAME TEMPERATURES

Mix	Before burning	400 °C	600 °C	800 °C
GLRef.	2.74	2.58	1.75	1.08
GLBF0.5%	3.25	3.15	2.20	1.67
GLBF0.75%	3.5	3.34	2.45	1.94
GLBF1%	3.76	3.63	2.80	2.23

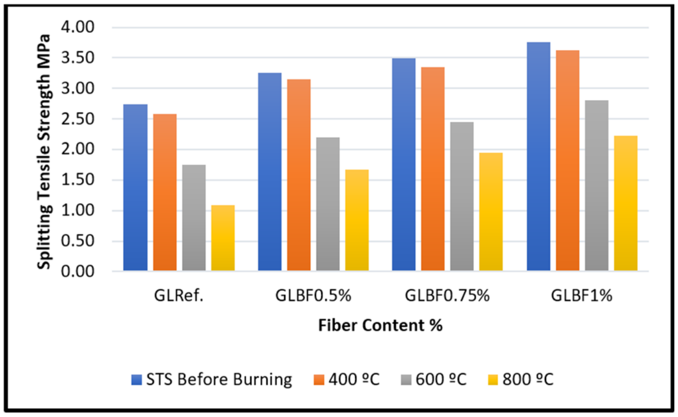

Fig. 5. Splitting tensile Strength of geopolymer lightweight concrete with different basalt fiber contents exposed to different fire flame temperatures.

C. Flexural Strength

As shown in Table IX and Figure 6, the flexural strength values increased in proportion to the increase in the basalt fiber content in the concrete specimens [35]. According to the experimental findings, the flexural strength of the unreinforced geopolymer lightweight concrete decreased by 4.2% following the exposure to a 400 °C fire flame. The specimens reinforced with 0.5%, 0.75%, and 1% basalt fiber exhibited a decrease of 3%, 2.8%, and 3.4%, respectively. At a temperature of 600 °C, the compressive strength exhibited a notable decrease, with drops of 36%, 27.8%, 23.6%, and 19.8% for the reference sample, and 0.5%, 0.75%, and 1% for the basalt fiber-reinforced samples, respectively. The exposure to 800 °C for an extend period resulted in the most substantial degradation, with strength reductions of 54.4%, 44.9%, 39.3%, and 32.9%, respectively, for the specified mixes. The elevated fiber content exhibited a minor mitigating effect at 400°C; however, higher temperatures (600°C and 800°C) resulted in increasing degradation [36], highlighting the limitations of basalt fiber reinforcement under extreme thermal conditions.

TABLE IX. RESULTS OF FLEXURAL STRENGTH EXPOSED TO DIFFERENT FIRE FLAME TEMPERATURES

Mix	Before burning	400 °C	600 °C	800 °C
GLRef.	3.51	3.36	2.24	1.6
GLBF0.5%	4.21	4.08	3.04	2.32
GLBF0.75%	4.61	4.48	3.52	2.8
GLBF1%	4.89	4.72	3.92	3.28

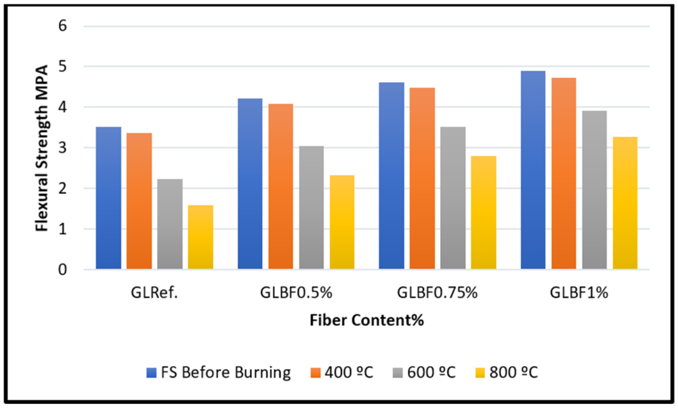

Fig. 6. Flexural Strength of geopolymer lightweight concrete with different basalt fiber content exposed to different fire flame temperatures.

VI. CONCLUSIONS

The objective of this study was to improve the mechanical properties of geopolymer lightweight concrete, which is frequently characterized by brittleness and necessitates greater attention during the design stage of the mixture. Basalt fiber was integrated into this geopolymer lightweight concrete at varying proportions (0.5%, 0.75%, and 1%) to ascertain its impact on strength development, enhancing the mechanical properties of concrete:

- Geopolymer lightweight concrete is a material that is susceptible to variations in the mix design and the curing process, necessitating precise handling during its production.
- According to the findings of the tests conducted, the compressive strength of unreinforced geopolymer lightweight concrete was reduced by 4.76% following the exposure to fire at 400 °C. The samples reinforced with 0.5%, 0.75%, and 1% basalt fiber exhibited a reduction in

weight of 2.9%, 2.52%, and 1.1%, respectively, at the same temperature. At 600 °C, 0.5%, 0.75%, and 1% the basalt fiber-reinforced samples exhibited a loss of 32%, 24.9%, 23%, and 19.1% in compressive strength, respectively. Further exposure to 800 °C resulted in significant damage to the mixes, with a 46%, 47.8%, 47.1%, and 45.9% decrease in strength, respectively.

- The testing results showed that a 400 °C fire flame led to a 5.8% reduction in the splitting tensile strength of unreinforced geopolymer lightweight concrete. The addition of basalt fiber at concentrations of 0.5%, 0.75%, or 1% resulted in a reduction of the specimens' mass by 3.15%, 3.34%, and 3.36%, respectively, at a constant temperature. At 600 °C, the reference, 0.5%, 0.75%, and 1% basalt fiber-reinforced samples exhibited a loss of 36%, 32.4%, 29.9%, and 25.4% in compressive strength, respectively. The maximum degradation temperature was determined to be 800°C, at which point the mixtures experienced a loss of strength equivalent to 60.5%, 48.5%, 44.4%, and 40.7%, respectively.
- The experimental findings demonstrated that the exposure to a fire at 400°C resulted in a 4.2% reduction in the flexural strength of geopolymer lightweight concrete that lacked reinforcement. The samples reinforced with 0.5%, 0.75%, and 1% basalt fiber exhibited a 3%, 2.8%, and 3.4% decrease in tensile strength at the same temperature, respectively. At 600°C, 0.5%, 0.75%, and 1% the basalt fiber-reinforced samples exhibited a loss of 36%, 27.8%, 23.6%, and 19.8%, respectively, in compressive strength. The extended exposure to temperatures of 800 °C caused the most damage to the blends, resulting in a significant reduction in strength by 54.4%, 44.9%, 39.3%, and 32.9%, respectively.

REFERENCES

[1] C. O. Nwankwo, G. O. Bamigboye, I. E. E. Davies, and T. A. Michaels, "High volume Portland cement replacement: A review," *Construction and Building Materials*, vol. 260, Nov. 2020, Art. no. 120445, https://doi.org/10.1016/j.conbuildmat.2020.120445.

[2] A. Khaloo, E. Molaei Raisi, P. Hosseini, and H. Tahsiri, "Mechanical performance of self-compacting concrete reinforced with steel fibers," *Construction and Building Materials*, vol. 51, pp. 179–186, Jan. 2014, https://doi.org/10.1016/j.conbuildmat.2013.10.054.

[3] R. Alzeebaree, A. Çevik, B. Nematollahi, J. Sanjayan, A. Mohammedameen, and M. E. Gülşan, "Mechanical properties and durability of unconfined and confined geopolymer concrete with fiber reinforced polymers exposed to sulfuric acid," *Construction and Building Materials*, vol. 215, pp. 1015–1032, Aug. 2019, https://doi.org/10.1016/j.conbuildmat.2019.04.165.

[4] K.-H. Yang, J.-K. Song, and J.-S. Lee, "Properties of alkali-activated mortar and concrete using lightweight aggregates," *Materials and Structures*, vol. 43, no. 3, pp. 403–416, Apr. 2010, https://doi.org/10.1617/s11527-009-9499-6.

[5] S. H. Mohammed and N. M. Fawzi, "The Effect of the Utilization of Sustainable Materials on Some Mechanical Properties of Geopolymer Mortar," *Engineering, Technology & Applied Science Research*, vol. 14, no. 1, pp. 12464–12469, Feb. 2024, https://doi.org/10.48084/etasr.6378.

[6] Y. Mohammadi, S. P. Singh, and S. K. Kaushik, "Properties of steel fibrous concrete containing mixed fibres in fresh and hardened state," *Construction and Building Materials*, vol. 22, no. 5, pp. 956–965, May 2008, https://doi.org/10.1016/j.conbuildmat.2006.12.004.

[7] N. M. Fawzi, K. I. Aziz, and S. M. Hama, "Effect of Metakaolin on Properties of Lightweight Porcelinate Aggregate Concrete," *Journal of Engineering*, vol. 19, no. 04, pp. 439–452, Apr. 2013, https://doi.org/10.31026/j.eng.2013.04.02.

[8] O. A. Abdulkareem, A. M. M. A. Bakri, H. Kamarudin, and I. K. Nizar, "A Study on the Synthesis of Fly Ash-Based Lightweight Aggregate Geopolymer Concrete," *Advanced Science Letters*, vol. 19, no. 1, pp. 282–285, Jan. 2013, https://doi.org/10.1166/asl.2013.4720.

[9] M. Mouli and H. Khelafi, "Performance characteristics of lightweight aggregate concrete containing natural pozzolan," *Building and Environment*, vol. 43, no. 1, pp. 31–36, Jan. 2008, https://doi.org/10.1016/j.buildenv.2006.11.038.

[10] J. Zhao, J. Zheng, G. Peng, and P. Sun, "Spalling and cracking modelling of high-performance concrete exposed to elevated temperatures," *Magazine of Concrete Research*, vol. 69, no. 24, pp. 1276–1287, Dec. 2017, https://doi.org/10.1680/jmacr.16.00139.

[11] A. Nazari *et al.*, "Corrigendum to Thermal shock reactions of ordinary portland cement and geopolymer concrete: Microstructural and mechanical investigation," *Construction and Building Materials*, vol. 304, Oct. 2021, Art. no. 124151, https://doi.org/10.1016/j.conbuildmat.2021.124151.

[12] L. Vickers, W. D. A. Rickard, and A. van Riessen, "Strategies to control the high temperature shrinkage of fly ash based geopolymers," *Thermochimica Acta*, vol. 580, pp. 20–27, Mar. 2014, https://doi.org/10.1016/j.tca.2014.01.020.

[13] P. K. Sarker, S. Kelly, and Z. Yao, "Effect of fire exposure on cracking, spalling and residual strength of fly ash geopolymer concrete," *Materials & Design*, vol. 63, pp. 584–592, Nov. 2014, https://doi.org/10.1016/j.matdes.2014.06.059.

[14] A. A. Hammadi, A. F. Izzat, and J. A. Farhan, "Effect of Fire Flame (High Temperature) on the Self Compacted Concrete (SCC) One Way Slabs," *Journal of Engineering*, vol. 18, no. 10, pp. 1083–1099, Oct. 2012, https://doi.org/10.31026/j.eng.2012.10.01.

[15] R. K. Aboud, H. K. Awad, and S. D. Mohammed, "Fire flame effect on the compressive strength of reactive powder concrete using different methods of cooling," *IOP Conference Series: Materials Science and Engineering*, vol. 518, no. 2, Feb. 2019, Art. no. 022029, https://doi.org/10.1088/1757-899X/518/2/022029.

[16] W. Mastura Wan Ibrahim, M. Mustafa Al Bakri Abdullah, R. Ahmad, A. Naveed, C. Mohd Ruzaidi Ghazali, and M. Ibrahim, "Effects of Thermal Resistance to Fly Ash-Based Lightweight Geopolymer," *IOP Conference Series: Materials Science and Engineering*, vol. 551, no. 1, Dec. 2019, Art. no. 012082, https://doi.org/10.1088/1757-899X/551/1/012082.

[17] M. M. Kadhum and N. M. F. Alwaan, "Behaviour of Fire Exposed Reinforced Concrete Rigid Beams with Restrained Ends," *Journal of Engineering*, vol. 19, no. 03, pp. 388–402, Mar. 2013, https://doi.org/10.31026/j.eng.2013.03.08.

[18] B. Q. Naeem and H. K. Awad, "Effect of Perlite Aggregate Replacement of Coarse Aggregate on the Behavior of SCC Exposed to Fire Flame by Using Different Cooling Methods," *Journal of Engineering*, vol. 31, no. 1, pp. 54–72, Jan. 2025, https://doi.org/10.31026/j.eng.2025.01.04.

[19] *C618-22 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*. West Conshohocken, PA, USA: ASTM International, 2023.

[20] *C989/C989M-18a Standard Specification for Slag Cement for Use in Concrete and Mortars*. West Conshohocken, PA, USA: ASTM International, 2018.

[21] *E291-18 Standard Test Methods for Chemical Analysis of Caustic Soda and Caustic Potash (Sodium Hydroxide and Potassium Hydroxide)*. West Conshohocken, PA, USA: ASTM International, 2009.

[22] *IQS 1703 Water Used for Concrete and Mortar*. Baghdad, Iraq: Central Organization for Standardization and Quality Control, 1992.

[23] *C330/C330M-14 Standard Specification for Lightweight Aggregates for Structural Concrete*. West Conshohocken, PA, USA: ASTM International, 2017.

[24] *IQS 45 Aggregate from Natural Sources for Concrete and Construction*. Baghdad, Iraq: Central Organization for Standardization and Quality Control, 1984.

[25] C494/C494M-17 Standard Specification for Chemical Admixtures for Concrete. West Conshohocken, PA, USA: ASTM International, 2019.

[26] R. Rawat and D. Pasla, "Mix design of FA-GGBS based lightweight geopolymer concrete incorporating sintered fly ash aggregate as coarse aggregate," *Journal of Sustainable Cement-Based Materials*, vol. 13, no. 8, pp. 1164–1179, Aug. 2024, https://doi.org/10.1080/21650373.2024.2361266.

[27] M. Rabie, M. R. Irshidat, and N. Al-Nuaimi, "Ambient and Heat-Cured Geopolymer Composites: Mix Design Optimization and Life Cycle Assessment," *Sustainability*, vol. 14, no. 9, Jan. 2022, Art. no. 4942, https://doi.org/10.3390/su14094942.

[28] *E119-20 Standard Test Methods for Fire Tests of Building Construction and Materials*. West Conshohocken, PA, USA: ASTM International, 2019.

[29] *EN 12390-3:2019 Testing hardened concrete - Part 3: Compressive strength of test specimens*. London, UK: BSI, 2019.

[30] *C496-96 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. West Conshohocken, PA, USA: ASTM International, 2017.

[31] *C293/C293M-16 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading)*. West Conshohocken, PA, USA: ASTM International, 2016.

[32] S. S. Hussein and N. M. Fawzi, "Behavior of Geopolymer Concrete Reinforced by Sustainable Copper Fiber," *IOP Conference Series: Earth and Environmental Science*, vol. 856, no. 1, Jun. 2021, Art. no. 012022, https://doi.org/10.1088/1755-1315/856/1/012022.

[33] O. A. Abdulkareem, A. M. M. A. Bakri, H. Kamarudin, and I. K. Nizar, "Fire Resistance Evaluation of Lightweight Geopolymer Concrete System Exposed to Elevated Temperatures of 100-800 °C," *Key Engineering Materials*, vol. 594–595, pp. 427–432, 2014, https://doi.org/10.4028/www.scientific.net/KEM.594-595.427.

[34] A. S. Elkhouly, A. M. Ahmed, and G. M. Ghanem, "Splitting Tensile Strength of Geopolymer Concrete Exposed to Fire," *Civil Engineering Research Magazine*, vol. 44, no. 2, pp. 88–99, Apr. 2022.

[35] M. S. Amouri and N. M. Fawzi, "The Effect of Different Curing Temperatures on the Properties of Geopolymer Reinforced with Micro Steel Fibers," *Engineering, Technology & Applied Science Research*, vol. 12, no. 1, pp. 8029–8032, Feb. 2022, https://doi.org/10.48084/etasr.4629.

[36] M. Ziada, S. Erdem, Y. Tammam, S. Kara, and R. A. G. Lezcano, "The Effect of Basalt Fiber on Mechanical, Microstructural, and High-Temperature Properties of Fly Ash-Based and Basalt Powder Waste-Filled Sustainable Geopolymer Mortar," *Sustainability*, vol. 13, no. 22, Jan. 2021, Art. no. 12610, https://doi.org/10.3390/su132212610.