The Impact of Utilizing Sustainable Ground Granulated Blast-Furnace Slag and Reinforced Basalt Fibers on the Mechanical Characteristics of Geopolymer Concrete

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ABSTRACT

Geopolymer Concrete (GPC) is a material with low carbon dioxide (CO_2) emissions utilized in the cement-production industry. This study produced GPC using 30% Fly Ash (FA) and 70% Ground Granulated Blast-Furnace Slag (GGBFS). The alkaline activation solution was made up of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). The mineral sodium silicate weighs 2.5:1 compared to sodium hydroxide. For the reinforcement Basalt Fibers (BFs) were utilized at volume fractions of 0.5%, 0.75%, and 1%. To cure the GPC specimens, they were heated in an oven for 4 hours at 70°C over 2 days. The GPC mixture with 1% BFs showed the greatest enhancement in compressive strength, that is, by 64.650 and 75.641 MPa. Flexural strength increased by 60.3% - 69.8% compared to the reference mix after 7 - 28 days of curing. At 28 days, the results of the tests on water absorption, void content, and bulk density were 1.383%, 1.116%, and 2535 kg/m³, respectively. BF utilization significantly improved GPC mechanical performance qualities.

Keywords-geopolymer concrete; ground granulated blas-furnace slag; fly ash; basalt fibers

I. INTRODUCTION

The manufacture of cement for concrete use is a significant contributor to CO_2 emissions. Almost one ton of CO_2 is released to the atmosphere for every ton of cement produced, representing 7% of the global CO_2 emissions. It is, therefore, essential to find technical and physical components utilized in concrete, which are friendly to the environment and simultaneously reduce the latter. Both CO_2 emissions from cement production and industrial waste can be recycled and cut down, reducing the environmental damage they cause [1]. Waste and supplemental cementitious materials (rice husk ash, silica fume, FA, blast-furnace slag, metakaolin) may function as substitutes for Portland cement [2]. These chemicals enhance concrete durability, reduce the likelihood of fracturing caused by heat in mass concrete, and need less energy for their production, which also leads to lower CO2 emissions. Great efforts have been made to create geopolymers as an innovative and ecologically viable alternative to Portland cement [3].

GPC is a novel component in the building industry, with an increased focus on the technical specifications of its production. The basic mix design of GPC consists of 60% GGBFS, 40% FA and Water Glass (WG) as a geopolymerization activator. Several attempts have been made to increase the proportion of GGBFS in the mix in order to increase GPC compressive strength [4, 5].

In [6, 7], conventional concrete was compared with GPC using FA and GGBFS as binder materials. The compressive strength and split tensile strength of the GPC sample was assessed after 28 days. The results indicated that the mixture including GGBFS had a strength comparable to that of standard concrete. The flexural strength of GPC was 50% better and the split tensile strength was analogous to that of traditional concrete. Authors in [8] studied the impact of geopolymer mortar reinforcement using 1% micro steel fibers, slag to FA ratio of 50:50, and a curing temperature of 240 C°. The geopolymer mortar showed better compressive strength performance by 8%, 22%, and 29% for a curing period of 3, 7, and 28 days, respectively. Authors in [9] studied a GPC design with a mix of 70% FA, 30% GGBFS, and sodium hydroxide blended with sodium silicate in a 2.5:1 proportion. Rice husk fibers were added at 1%. The sample was cured at 60 °C. The results indicated that the compressive strength increased by 35% and 42% after curing for 7 and 28 days, respectively.

The objectives of the current investigation are:

- To decrease global CO_2 emissions while promoting the maintenance and expansion of concrete industry sustainable development.
- To produce GPC from recycling waste materials, like FA and slag, which would otherwise end up in landfills.
- To study the influence of GGBSF and BF-reinforced GPC on the mechanical characteristics of the produced concrete.

II. MATERIAL

A. Fly Ash

The FA was designed as class F with iron oxide, silica, and alumina. The criteria were established according to ASTM C618-19 [10], as presented in Table I.

TABLE I. CHEMICAL SPECIFICATIONS OF FA

Oxide	Content %	ASTM C618-19 type F Requirement
Fe_2O_3	5.31	Sum of value more than 70%
Al_2O_3	17.75	
SiO2	64.73	
SO3	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%

B. Ground Granulated Blast-Furnace Slag

GGBFS is a byproduct of the production process. It is generated with a quick cooling of the liquid iron byproduct taken from a blast burner using water or steam. The utilized temperatures ranged from 1500 ℃ to 1600 ℃ and the chemical specifications of GGBFS, as stipulated by the ASTM C618-19, are denoted in Table II.

TABLE II. CHEMICAL SPECIFICATIONS OF GGBFS

Oxide	Content %	ASTM C618-19 type F requirement
Fe_2O_3	0.5	Sum of value more than 70%
Al_2O_3	25.53	
SiO2	45.88	
SO3	1.98	Maximum 5%
MgO	1.87	---
CaO	19.24	Maximum 18%
K_2O	1.8	---
Na_2O	0.8	---
L.O.I	2.53	Maximum 6%

*According the manufacturer's datasheet

C. Sodium Hydroxide (NaOH)

The Sodiume Hydroxid flakes available for commercial use possess a purity level of 98%. When dissolved in filtered water, they provide a concentrated solution, as detailed in ASTM E291-2009 [11].

D. Sodium Silicate (Na_2SiO_3)

The correct amount of Na_2SiO_3 was found through comparing the amounts of sodium oxide, silicon dioxide, and H_2O. The Na_2SiO_3 used in the mixture,was supplied by Sika.

E. Water

A distilled water mixture was utilized to dissolve the flakes of caustic soda, producing a sodium hydroxide solution as specified in IQS 1703-2018 [12].

F. Fine Aggregate

Zone 2 sand was employed as the fine aggregate according to the specifications of IQS 45-1980, as illustrated in Table III. The fineness modulus was measured as 2.84 [13].

TABLE III. FINE AGGREGATE SIEVE ANALYSIS

Sieve mm.	Accumulative passing (%)	IQS 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

G. Coarse Aggregate

In this experimental study,coarse aggregate with a specific gravity value of 2.6 and according to the specifiications of IQS 45-1980, as shown inTable IV, was used.

TABLE IV. COARSE AGGREGATE SIZE

Sieve mm.	Accumulative passing (%)	Limit of IQS 45-1980 nominal size 10mm
14	100	100
10	93	85-100
4.75	6	0-25
2.36	1	0-5

H. Basalt Fiber

The BF source is natural volcanic ejecta. BF is an inorganic fiber material that undergoes processing at high temperatures between 1500 and 1700 °C. BF characteristics are shown in Table V, and a ample can be seen in Figure 1.

TABLE V. BF CHARACTERISTICS

Characteristics	Value
Chopped diameter µm	13
Chopped length mm	12
Tensile strength (MPa)	2600-4840
Specific gravity g/cm3	2.6-2.8

I. Superplasticizers (SPs)

SPs improve concrete workability, flexural and compressive strength, and reduce shrinkage. The dosage should be 0.5 - 2.5 kg SPs per 100 kg of cement, complying with the requirements of ASTM C 494-13, which defines Type G admixtures [14].

Fig. 1. BF sample.

III. GEOPOLYMER CONCRETE DESIGN

A. Preparation of Alkaline Solution

The molar concentration of sodium hydroxide has been set at 12 molars. After mixing and cooling the composite, the sodium silicate was added and the activator solution was established for 24 hours, with a sodium silicate to sodium hydroxide ratio of 2.5:1. There was a 0.4 ratio of this solution to cementitious components.

B. Mixing

An alkaline solution was combined with an SP prior to its application. The dry constituents were combined manually for 2 min before adding the alkaline liquid to all mixtures with the use of (750 kg/m3) cementitious material (70% GGBFS, 30% FA), as presented in Table VI. The mixture was repeated with 2% SP and 10% tap water. Homogeneity was achieved after 10-15 min. An electric mixer was utilized for mixing. Concrete layers were applied to molds in accordance with ASTM C192/192M-2019 [15]. The specimens were compressed and smoothed to achieve a consistent humidity level.

TABLE VI. MIX OF GPC FOR 1M3 - WEIGHT (kg/m^3)

Mix type	Slag	FA	Na2SiO3	NaOH	Coarse Agg.	Fine Agg.	BF (%)
GR	525	225	214	85.5	945	728	0
G1	525	225	214	85.5	945	728	0.5
G2	525	225	214	85.5	945	728	0.75
G3	525	225	214	85.5	945	728	1

C. Curing

After casting, the specimens were placed in an oven at a designated temperature of 70 °C for 4 hours over 2 days. The specimens underwent testing after 7 and 28 days.

D. Testing Of Geopolymer Concrete Specimens

1) Slump Test

The present study employs slump tests to assess workability according to ASTM C143-2020 [16].

2) Compressive Strength

The conducted GPC compressive strength test complied with BS-EN-12390-3:2019 [17]. A cube of 100 × 100 ×x 100 mm^3 size was used along with a hydro mechanical testing apparatus capable of 2000 kN and 2.5 MPa/s loading rate, as shown in Figure 2. The compressive strength was calculated by:

$$p = \frac{fc}{Ac} \quad (1)$$

where p is the compressive strength (MPa), fc is the maximum applied force (N), and Ac is the cross-section area (mm^2).

Fig. 2. Cube inside the compressive strength apparatus.

3) Flexural Strength

The flexural test was conducted in accordance with the ASTM C293-2002, to evaluate the one-point load flexural strength of the GPC, as depicted in Figure 3. The specimens (400 × 80 × 80) mm^3 were tested after 7 and 28 days. Flexural strength was calculated by [18]:

$$R = \frac{3pl}{2bd^2} \quad (2)$$

where R is the flexural strength (MPa), p is the maximum load (N), l is the length of the span (mm), b is the specimen thickness (mm), and d is the mean prism thickness (mm).

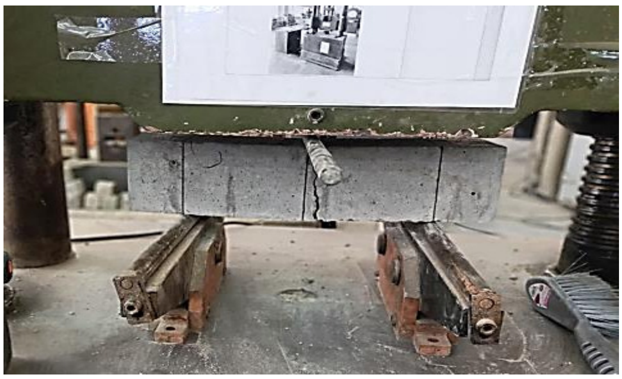

Fig. 3. Prism in the flexural strength testing machine.

We also performed the examination 2000 kN, as shown in Figure 4. The tensile strength was determined using:

$$fst = \frac{2P}{\pi dl} \quad (3)$$

where f_{st} is the indirect splitting strength (MPa), p is the maximum applied force of testing apparatus (N), d is the diameter of the cylinder (mm), and l is the length of the cylinder (mm).

Fig. 4. Cylinder in the splitting tensile strength testing machine.

4) Bulk Density, Absorption, Void Content

This test was conducted on three specimens after curing, according to ASTM C642-2017 [20], with and without BFs. Density, water absorption, and void content were calculated by:

$$\text{Bulk density, dry} = [A/(C-D)] \times \rho \quad (4)$$

$$\text{Water absorption percent} = [(B-A)/A] \times 100 \quad (5)$$

$$\text{Voids } (\%) = [(C-A)/(C-D)] \times 100 \quad (6)$$

where A is the equivalent to the weight of the dried in the oven specimens in air (g), B denotes the mass of the surface of the dry specimens in the atmosphere (g), C denotes the mass of the surface of the dry sample in air, following immersion and boiling (g), D denotes the observed weight of a specimen in water after submersion and boiling (g), and ρ is the density of water (1 g/cm^3).

IV. RESULTS AND DISCUSSION

A. Fresh Proprieties of Geopolymer Concrete

1) Slump test

GPC exhibited significant slump values. This is due to the comparatively elevated viscosity that the activator solution employed in GPC, as portrayed in Figure 5.

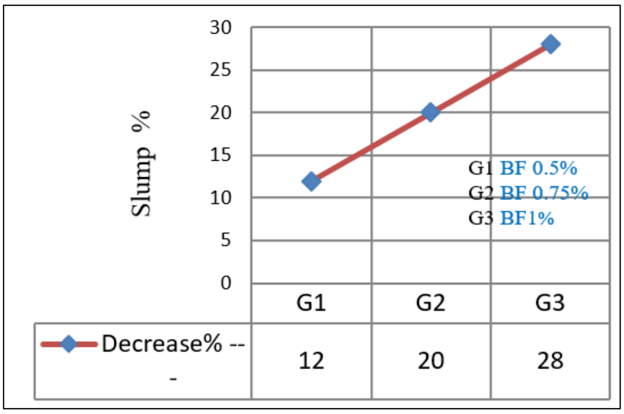

Fig. 5. Slump percentage to mix.

B. Mechanical Properties Of Geopolymer Concrete

1) Compressive Strength

The compressive strength test was carried out at 7 and 28 days. The outcomes are displayed in Table VII and Figure 6, demonstrating that the compressive strength of all samples consistently enhanced by age. GPC exhibits an early high strength due to rapid pozzolanic reactions. The former gets almost 70-80% of its compressive strength within 7 days. When increasing the BF ratio by 1%, a 10% increase in compressive strength is achieved because the fibers improve the force distribution and prevent cracking [22].

TABLE VII. COMPRESSIVE STRENGTH RESULTS

Compressive strength MPa				
Mix type	**7 days**	**Increase %**	**28 days**	**Increase %**
GR	58.900	----	68.780	---
G1	61.381	4.2	72.430	5.3
G2	63.963	8.5	73.805	7.3
G3	64.650	9.7	75.641	10

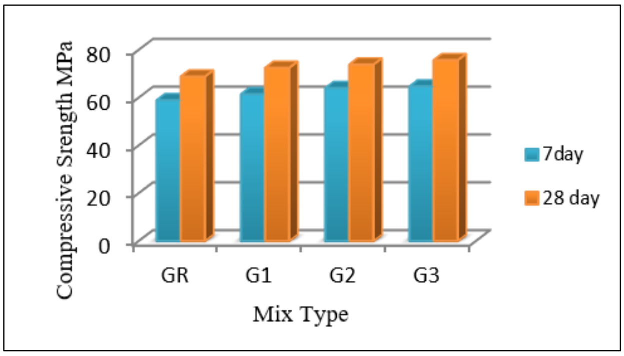

Fig. 6. Correlation between mixes and compressive strength.

2) Flexural Strength

The outcomes of the flexural strength test demonstrated a beneficial impact on flexural strength, attributable to fiber inclusion, as illustrated in Table VIII and Figure 7. The fibers operate within the concrete as a connector, inhibiting crack propagation and postponing their initiation and growth [23]. An increase in flexural strength of 56% was found after 28 days of curing. The increasing BF proportion correlates with flexural strength improvement. The interface relationship among fibers and their matrix allows the former to endure the load after matrix failure.

TABLE VIII. FLEXURAL STRENGTH RESULTS

Flexural strength MPa				
Mix type	**7 days**	**Increase (%)**	**28 days**	**Increase (%)**
GR	4.929	----	5.783	---
G1	6.212	26%	7.620	30%
G2	7.030	42.6%	8.163	41%
G3	7.901	60.3%	9.821	69.8%

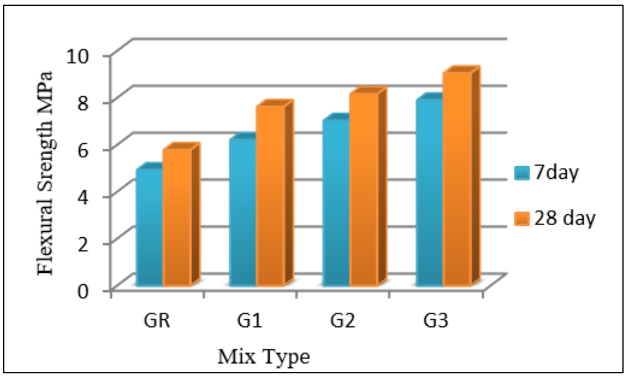

Fig. 7. Correlation between mix type and flexural strength.

3) *Splitting Tensile Strength Test*

The results exibited how BFs enhanced splitting tensile strength, as displayed in Table IX and Figure 8. The fibers bridge the cracks by preventing the propagation crack width when microcracks begin to form under tensile strength. They distribute the load and prevent the forming of a widening, which delays a possible failure and increases the energy absorption capacity of concrete. This leads to an improvement of the fiber to matrix bonding, which plays the basic role in the enhancement of the splitting tensile strength performance when compared with a GPC without fibers [24]. The mixes containing BFs at a ratio of 1% by volume, exhibit an increase in splitting tensile strength by 60.3% and 56.4% at 7 and 28 days of age compared with the reference mix, GR, which has no fibers.

TABLE IX. SPLITTING STRENGTH RESULTS

Splitting tensile strength MPa				
Mix type	**7 days**	**Increase (%)**	**28 days**	**Increase (%)**
GR	3.278	---	4.112	---
G1	4.137	24%	5.360	23.8%
G2	5.010	44%	6.221	44.4%
G3	5.927	55.2%	6.790	47.6%

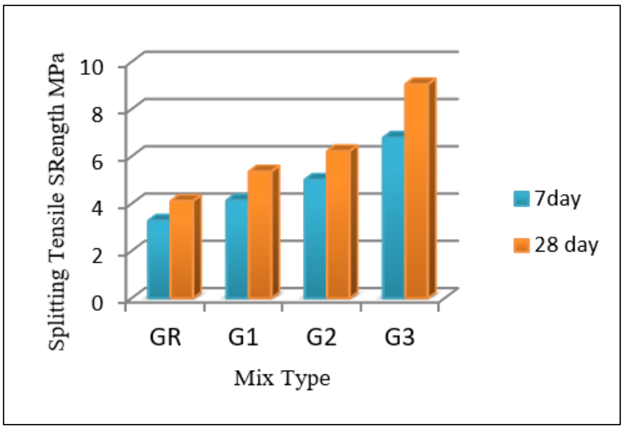

Fig. 8. Connection between mixes and splitting tensile strength.

4) *Water Absorption, Void Content, Bulk Density*

The mixes GR, G1, G2, and G3 were tested to calculate their water absorption, void content, and bulk density at the 28th day. The results are presented in Table X and Figures 9 and 10. All mixtures absorbed less water with time. However, adding BFs increased water absorption, owing to the gaps around fibers. Void content in all mixture combinations diminished with age, since GPC usually involves slag and FA, which lowers the void content [25].

In practice, geopolymer density is close to normal concrete's. The former varies in the range of 2200-2600 kg/m^3, but as the polymerization rate of the process continues, there is an improvement in the microstructure, leading to denser GPC substances [26].

TABLE X. WATER ABSORPTION, VOID CONTENT, AND BULK DENSITY TEST RESULTS

Mix type	Water absorption (%)	Void content (%)	Density (kg/m^3)
GR	0.670	0.223	2474
G1	0.736	0.491	2497
G2	0.995	0.802	2510
G3	1.383	1.116	2527

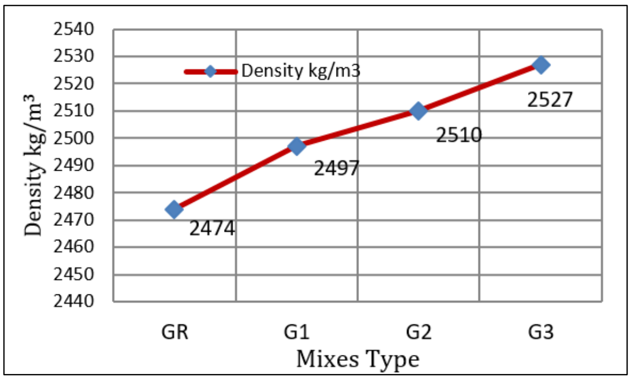

Fig. 9. Relationship between mix type and bulk density.

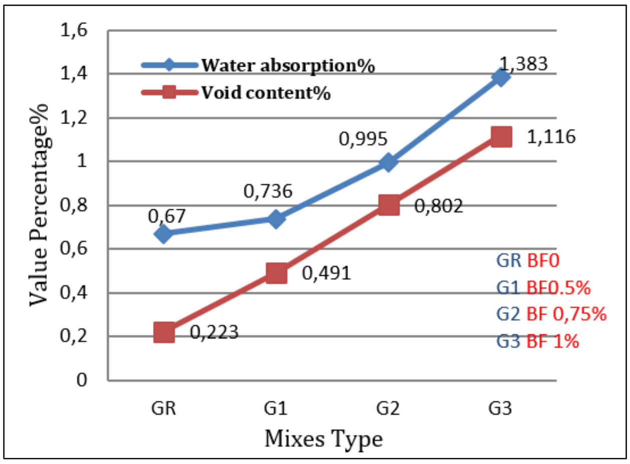

Fig. 10. Water absorption and void content percentages between mixes.

V. CONCLUSION

Geopolymer Concrete (GPC) based on slag and Fly Ash (FA), is considered one of the greatest alternatives to normal concrete. In this study, GPC was reinforced with Basalt Fibers (BFs) at 0.5%, 0.75%, and 1% concentrations, which improved its mechanical property performance.

Regarding GPC workability, the slump test findings for renewed GPC showed a decrease of 12%, 20%, and 28% for 0.5%, 0.75%, and 1% BFs, respectively compared to the reference mix slump of 250 mm. The use of Superplasticizers (SPs) in conjunction with fiber reinforcement can mitigate the reduction in workability. When used along with fibers, SPs help to offset the drop in workability. GPC, which accelerates strength development at an early age, is suited for heat curing at 70 °C. The flexural strength was increased by 60.3% and the splitting tensile strength by 65.3% compared with the reference mix. The compressive strength was increased by 9.7% and 10%, respectively. At 28 days of age, when the BF ratio was 1%, there was a water absorption of 1.383%, a void content of 1.116%, and a bulk density of 2535 kg/m³. The presence of Ground Granulated Blast-Furnace Slag (GGBFS) resulted in a denser microstructure, reduced porosity, and enhanced durability. The addition of GGBFS at 70% ratio in GPC led to a substantial improvement in the material's mechanical characteristics that reaches an ideal level.

REFERENCES

[1] Z. F. Muhsin and N. M. Fawzi, "Effect of Fly Ash on Some Properties of Reactive Powder Concrete," *Journal of Engineering*, vol. 27, no. 11, pp. 32–46, Nov. 2021, https://doi.org/10.31026/j.eng.2021.11.03.

[2] W. Li, E. D. Shumuye, T. Shiying, Z. Wang, and K. Zerfu, "Eco-friendly fibre reinforced geopolymer concrete: A critical review on the microstructure and long-term durability properties," *Case Studies in Construction Materials*, vol. 16, no. e00894, Jun. 2022, https://doi.org/10.1016/j.cscm.2022.e00894.

[3] Y. Lin, C. Yang, H. Shi, Y. Wang, and Z. Zong, "Dynamic mechanical properties of one-part ultra-high performance geopolymer concrete," *Journal of Building Engineering*, vol. 95, no. 110173, Oct. 2024, https://doi.org/10.1016/j.jobe.2024.110173.

[4] R. Sangi, B. S. Sreenivas, and K. Shanker, "Mix Design of Fly Ash and GGBS based Geopolymer Concrete activated with Water Glass," *Engineering, Technology & Applied Science Research*, vol. 13, no. 5, pp. 11884–11889, Oct. 2023, https://doi.org/10.48084/etasr.6216.

[5] A. Rajarajeswari and G. Dhinakaran, "Compressive strength of GGBFS based GPC under thermal curing," *Construction and Building Materials*, vol. 126, pp. 552–559, Nov. 2016, https://doi.org/10.1016/j.conbuildmat. 2016.09.076.

[6] M. Yu, T. Wang, Y. Chi, D. Li, L. Li, and F. Shi, "Residual mechanical properties of GGBS-FA-SF blended geopolymer concrete after exposed to elevated temperatures," *Construction and Building Materials*, vol. 411, Jan. 2024, Art. no. 134378, https://doi.org/10.1016/j.conbuildmat. 2023.134378.

[7] R. M. Waqas, F. Butt, X. Zhu, T. Jiang, and R. F. Tufail, " A Comprehensive Study on the Factors Affecting the Workability and Mechanical Properties of Ambient Cured Fly Ash and Slag Based Geopolymer Concrete," *Applied Sciences*, vol. 11, no. 18, no. 8722, Jan. 2021, https://doi.org/10.3390/app11188722.

[8] M. S. Amouri and N. M. Fawzi, "Study The Impact of Geopolymer Mortar Reinforced by Micro Steel Fibers," *Journal of Engineering*, vol. 28, no. 11, pp. 56–66, Nov. 2022, https://doi.org/10.31026/j.eng. 2022.11.05.

[9] S. S. Hussein and N. M. Fawzi, "Influence of Using Various Percentages of Slag on Mechanical Properties of Fly Ash-based Geopolymer Concrete," *Journal of Engineering*, vol. 27, no. 10, pp. 50–67, Oct. 2021, https://doi.org/10.31026/j.eng.2021.10.04.

[10] "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete," ASTM C618-19, ASTM International, 2019.

[11] "Standard Test Methods for Chemical Analysis of Caustic Soda and Caustic Potash (Sodium Hydroxide and Potassium Hydroxide)," ASTM E291-09, ASTM International, 2009.

[12] "Water Used for Concrete and Mortar," Iraqi Specification No. 1703, Central Organization for Standardization and Quality Control, Baghdad, Iraq, 1992.

[13] "Aggregate from Natural Sources for Concrete and Construction," Iraqi Specification No. 45, Central Organization for Standardization and Quality Control, Baghdad, Iraq, 1980

[14] "Standard Specification for Chemical Admixtures for Concrete," ASTM C494/C494M-05, ASTM International, 2005.

[15] "Standard Practice for Making and Curing Concrete Test Specimens in the laboratory," ASTM C192/C192M-19, ASTM International, 2019.

[16] "Standard Test Method for Slump of Hydraulic-Cement Concrete," ASTM C143/ C143M-20, ASTM International, 2020 .

[17] "Testing Hardened Concrete – Compressive Strength of Test Specimens," BS EN 12390-3:2019 – TC, BSI, 2019.

[18] "Standard test method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)," ASTM C 293-2002, ASTM International, 2002.

[19] "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens," ASTM C496/C496M-17, ASTM International, 2017.

[20] "Standard Test Method for Density, Absorption and Voids in Hardened Concrete," ASTM C642-13, ASTM International, 2013.

[21] Y. Yu, L. Zhou, and L. Lin, "Compressive stress–strain relationship and its variability of basalt fiber reinforced recycled aggregate concrete," *AIP Advances*, vol. 14, no. 7, Art. no. 075320, Jul. 2024, https://doi.org/10.1063/5.0220434.

[22] K. P. Zubarev et al., "Structure and Properties Improvement by Recipe Factors of Geopolymer Basalt Fiber Reinforced Concrete for Building Enclosing Structures," *Buildings*, vol. 14, no. 3, Art. no. 743, Mar. 2024, https://doi.org/10.3390/buildings14030743.

[23] M. Rajendran, K. K. Athithan, and K. Bakthavatchalam, "Flexural behaviour of geopolymer concrete beams with hybrid natural–synthetic fibre reinforcement," *Magazine of Concrete Research*, vol. 76, no. 22, pp. 1290–1301, Nov. 2024, https://doi.org/10.1680/jmacr.23.00343.

[24] Y. Zhang, Y. Sun, W. Zhong, and L. Fan, "A Real-Time Study on the Cracking Characteristics of Polyvinyl Alcohol Fiber-Reinforced Geopolymer Composites under Splitting Tensile Load Based on High-Speed Digital Image Correlations," *Buildings*, vol. 14, no. 7, Art. no. 1986, Jul. 2024, https://doi.org/10.3390/buildings14071986.

[25] N. S. D. M. Azhar, F. F. Zainal, and M. M. A. B. Abdullah, "Effect of geopolymer paste on compressive strength, water absorption and porosity," *AIP Conference Proceedings*, vol. 2291, no. 1, Art. no. 020027, Nov. 2020, https://doi.org/10.1063/5.0023099.

[26] M. Olivia and H. Nikraz, "Properties of fly ash geopolymer concrete designed by Taguchi method," *Materials & Design (1980-2015)*, vol. 36, pp. 191–198, Apr. 2012, https://doi.org/10.1016/j.matdes.2011.10.036.