Effect of Basalt Fiber on the Mechanical Properties of Sustainable Geopolymer Lightweight Concrete

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ABSTRACT

Eco-friendly materials are increasingly used in civil engineering to support sustainable development. Conventional concrete relies heavily on Ordinary Portland Cement (OPC), the production of which contributes significantly to the carbon dioxide (CO_2) emissions. Ground Granulated Blast Furnace Slag (GGBFS) and fly ash can partially replace OPC, thereby reducing the environmental impact. This study investigates the effect of basalt fiber incorporation on the mechanical properties of geopolymer lightweight concrete. The concrete mixtures consisted of fly ash, slag, pumice aggregate, sand, and an alkaline activator prepared by combining sodium hydroxide and sodium silicate. The mix design included an activator-to-binder ratio of 0.45, sodium hydroxide molarity of 12 M, and a sodium hydroxide to sodium silicate ratio of 1:2.5. Basalt fiber was added at 0.5%, 0.75%, and 1% by volume. All specimens were cured at 80 °C for 24 h. The mechanical properties evaluated included compressive strength, splitting tensile strength, and flexural strength. The results showed that basalt fiber significantly improved all measured properties. At 28 days, the compressive strength increased by 11.67%, 14.85%, and 17.5%, the splitting tensile strength by 20%, 27.5%, and 38.75%, and the flexural strength by 21.6%, 32.14%, and 42.73%, respectively.

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

I. INTRODUCTION

Concrete production is one of the major contributors to the environmental pollution and CO_2 emissions worldwide. To reduce the negative environmental effects of CO_2 emissions, OPC alternatives should be established [1]. While encouraging the effective use of industrial waste, geopolymers may be a good alternative for lowering or eliminating the need for cement [2, 3]. When base materials rich in aluminosilicate are activated by alkalis, an inorganic polymer known as geopolymer is created [4]. The molarity of sodium hydroxide, the ratio of sodium hydroxide to sodium silicate, the binder concentration, and the solution content are among the variables involved in producing geopolymer lightweight concrete [5]. Due to the reduced total water content and higher rate of geopolymerization, increasing NaOH concentration from 8 to 12 M makes the geopolymer paste more viscous and raises the compressive strength [6].Various mix design variables for alkali-activated slag concrete have been investigated, showing favorable results compared to OPC [7].

Currently, geopolymers are widely utilized in the industrial sector as a suitable alternative and have been employed in various applications, such as precast beams, boat ramps, pavements, bricks, retaining walls, water tanks, and precast bridge decks [8]. In concrete construction, self-weight represents a significant portion of the total building load, making reduced concrete density advantageous. This reduction, while maintaining equivalent strength levels, lowers the dead load in structural and foundation design [9].

Geopolymer composites are characterized by good mechanical and physical properties, including low water absorption, high early compressive strength, and resistance to heat and fire. Since compressive strength is a critical structural design property, high early strength can offer additional advantages, such as reduced construction time and labor, as well as energy and formwork savings [10]. The common alkaline activator used in geopolymer concrete is a liquid combination of sodium or potassium hydroxide with sodium or potassium silicate [11, 12].

Pumice-based lightweight aggregate concrete can be used in various construction applications due to benefits, like low unit weight and improved insulation [13, 14]. However, mixing and placing concrete with lightweight aggregates is more difficult than with conventional aggregates [15]. Lightweight aggregates have low specific gravity and high porosity, and they tend to float and reduce cohesiveness, especially in fluid concrete mixtures [16-18]. Pumice is a notable natural lightweight aggregate due to its exceptional toughness and durability [19]. It has a granular shape and is formed when lava cools rapidly [20]. Higher pumice content leads to significant increases in compressive strength, and its behavior is often linearly correlated with the compressive strength [21]. The construction sector requires new improvements due to the rising demand; thus, the addition of fiber has become a key solution to address these needs [22, 23]. Basalt fibers are among the most environmentally sustainable and high-performance fibers, and they have been widely studied [24]. Because of their high tensile strength, basalt fibers are particularly valued [25]. The primary advantage of using basalt fibers is the shift from brittle failure to ductile behavior in concrete mixtures subjected to compressive loads [26].

The objective of this research is to achieve environmental benefits by reducing the CO_2 emissions from the cement industry while simultaneously producing high-quality, cost-effective concrete with enhanced strength. It investigates different basalt fiber volume fractions 0.5%, 0.75%, and 1% in geopolymer lightweight concrete by examining their effects on the compressive, splitting tensile, and flexural strength.

II. MATERIALS EMPLOYED

A. Fly Ash

The fly ash composition properties utilized in this investigation are shown in Table I. The investigation indicates that fly ash is classified as Type F and meets the ASTM C618, 2023 criteria [27].

TABLE I. CHEMICAL COMPOSITION OF FLY ASH AND ITS COMPLIANCE WITH ASTM C618

Oxides	**Contents %**	**Requirements according to ASTM C618 Type F**
SiO_2	46.65	≥50
Al_2O_3	25.09	
Fe_2O_3	5.47	
SO_3	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 is presented in Table II. The results indicate that the material used in this study complies with the requirements of ASTM C989 [28], confirming its appropriateness as a binder component in the geopolymer mixture. Due to its high calcium and silica content, GGBFS exhibits elevated reactivity, which promotes the gel formation and enhances the strength development when combined with alkaline activators.

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

Oxides	**Contents (%)**		**Requirement 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 (99% pure) were dissolved in distilled water to prepare the sodium hydroxide (NaOH) solution. The preparation method follows the guidelines of ASTM E291-2009 [29], ensuring consistency and accuracy in concentration. A molarity of 12 mol/L was used in this study.

D. Sodium silicate, Na_2SiO_3

The composition of sodium silicate solutions is determined by the Na_2O:SiO_2 molar ratio, which governs silicate polymerization, and the concentration is dictated by the H_2O content.

E. Water

The flake of NaOH requires distill water dissolution to produce the NaOH solution. However, Saturated Surface Dry (SSD) water was utilized to create the aggregate complied with IQS 1703-2018 [30]

F. Pumice

Pumice, a lightweight volcanic rock, was imported from Turkey and used as coarse aggregate in this research. The nominal size ranged from 12.5 mm to 4.75 mm. Table III presents the chemical composition of the lightweight pumice aggregates, while Table IV shows the gradation according to ASTM C330 [31].

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

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

G. Fine Aggregate

The fine aggregate used in this experiment was sand. As shown in Table V, it was categorized as zone four and found to comply with the specifications outlined in IQS (No. 45/1984) [32].

TABLE V. SIEVE ANALYSIS AND CHEMICAL COMPOSITION 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 utilized. The foundation of this superplasticizer is Poly-Carboxylate Ether, which adheres to the ASTM C494 Standard Type A and G [33].

I. Basalt Fiber

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

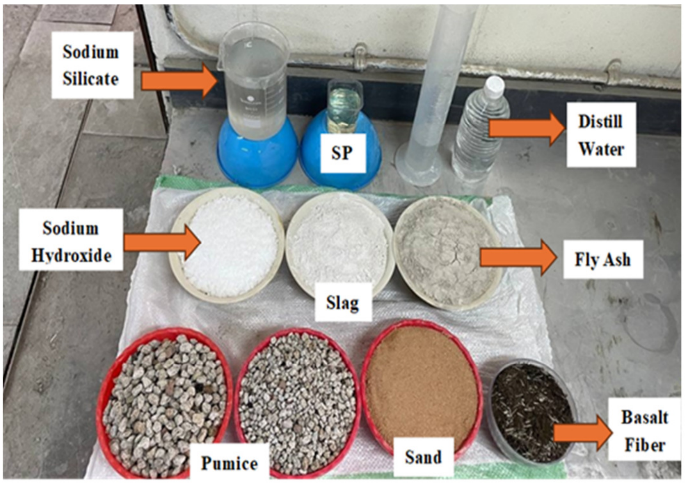

Fig. 1. Materials used in this study.

III. MANUFACTURE OF GEOPOLYMER LIGHTWEIGHT CONCRETE

1) Mixing

1. Mixing is a critical step in the production of geopolymer lightweight concrete. In this study, the mixing method developed in [34] was followed, using an electric mixer with a capacity of 0.01 m³.
2. After sieving, dust and other impurities were removed from the pumice and fine aggregates. All aggregates were in SSD condition.
3. The mixing procedure was as follows: The lightweight aggregate (pumice) and fine aggregate (sand) were mixed for 1 min in the mixer. One-quarter of the alkaline solution was then added and mixing continued for another min. After stopping the mixer, fly ash and GGBS were added to the mixture, and mixing proceeded for an additional min. The remaining three-quarters of the solution, pre-mixed with the specified dose of superplasticizer, were gradually added while mixing continued for three min. Finally, after stopping the mixer, the fresh geopolymer concrete was ready for mold casting.

After selecting the geopolymer lightweight concrete mixture, different volume fractions of basalt fiber (0.5%, 0.75%, and 1%) were added to evaluate their influence on the mechanical properties of the composite. Table VI presents the mix design of the geopolymer lightweight concrete in kg/m³. FA refers to Fly Ash, A/B is the Activator Solution to Binder Ratio, M is the Molarity, SH:SS denotes the Sodium Hydroxide to Sodium Silicate Ratio; and SP stands for the Superplasticizer.

TABLE VI. MIX PROPORTION FOR GEOPOLYMER LIGHTWEIGHT CONCRETE

Mix	**GL Ref**	**GLBF 0.5%**	**GLBF 0.75%**	**GLBF 1%**
FA	162	162	162	162
Slag	378	378	378	378
Pumice	530	530	530	530
Sand	450	450	450	450
A/B	0.45	0.45	0.45	0.45
M	12	12	12	12
SH: SS	1:2.5	1: 2.5	1: 2.5	1: 2.5
SP%	1.5	1.5	1.5	1.5
Basalt fiber	-	13.5	20.25	27

2) Curing

Concrete specimens were subjected to curing in the laboratory oven at 80 ℃ for 24 h, as illustrated in Figure 2. The experimental regime followed the specifications in [35]. The specimens were moved to another oven to cool and maintain the temperature until the test date.

Fig. 2. Placing the sample into the laboratory oven.

IV. TEST METHODS

A. Compressive Strength

The compressive strength was evaluated on 100x100x100 mm cube specimens in conformity with BS-EN-12390-3, 2019 [36]. The specimens were examining at 7 and 28 days. Each test assessed the mean compressive strength of three specimens. The Compressive Strength was calculated by:

$$f_c = \frac{P}{A} \tag{1}$$

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

B. Splitting Tensile Strength

The splitting tensile strength testing was performed in accordance with ASTM C496-17 [37]. Cylindrical specimens measuring 100×200 mm were tested at 7 and 28 days. The average value was calculated from three specimens using:

$$f_t = \frac{2*P}{\pi*l*d} \tag{2}$$

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

C. Flexural Strength

To determine the flexural strength, a center-point load test was performed on the geopolymer lightweight concrete in accordance with ASTM C293M-16. Tests were conducted at 7 and 28 days using the average of three prism specimens (75×75×380 mm), according to:

$$f_t = \frac{3*P*L}{2*b*d^2} \tag{3}$$

where f is the flexural strength (MPa), L is the span length (mm), P is the maximum applied load (N), b is the specimen width (mm), and d is the specimen depth (mm).

V. RESULTS AND DISCUSSION

A. Compressive Strength

A fundamental characteristic for hardened concrete is its compressive strength. Table VII and Figure 3 present the results of the compressive strength. Specimens reinforced with different ratios of basalt fibers (0.5, 0.75, 1%) showed a major enhancement in strength relative to GLRef. specimens, attributable to the fiber role as a bridging agent that limits or delays the cracking formation. In accordance with the test results, when the percentage of basalt fiber increases, the compressive strength increases too. Especially, when adding 0.5%, 0.75%, and 1% of basalt fiber, resulted in improvements in the compressive strength by 9.44%, 13.77%, and 16.53%, respectively, at 7 days, and improvements by 11.67%, 14.85%, and 17.5%, respectively, at 28 days. This increased the pores of the concrete in many orientations, due to the basalt fiber filling, resulting in enhanced strength properties [38].

TABLE VII. COMPRESSIVE STRENGTH RESULTS FOR 7 AND 28 DAYS

Mix	Compressive strength 7 days (MPa)	Compressive strength 28 days (MPa)
GLRef	25.4	29.6
GLBF 0.5%	27.8	32.9
GLBF 0.75%	28.9	33.8
GLBF 1%	29.6	34.6

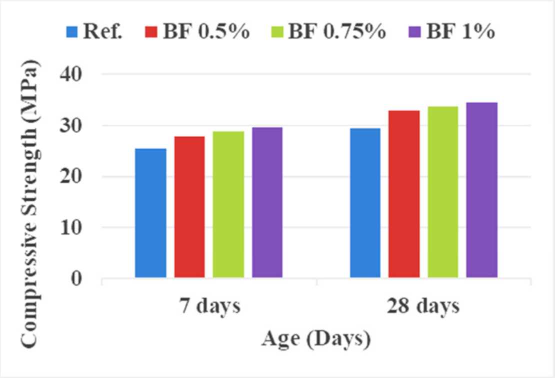

Fig. 3. Compressive strength of geopolymer lightweight concrete with different basalt fiber content at different ages.

B. Splitting Tensile Strength

Table VIII and Figure 4 present the outcomes of the splitting tensile strength test, demonstrating the improvement attributable to the fiber addition. Enhancing the composite matrix significantly improves its strength and stiffness. This reduces deformation and may modify or delay the composite failure mechanisms [39]. The splitting tensile strength rose with the addition of basalt fiber, showing enhancements of 18.57%, 29.28%, and 36.43% at 7 days, and 20%, 27.5%, and 38.75% at 28 days, respectively.

TABLE VIII. SPLITTING TENSILE STRENGTH RESULTS FOR 7 AND 28 DAYS

Mix	Splitting tensile strength 7 days (MPa)	Splitting tensile strength 28 days (MPa)
GLRef.	2.23	2.55
GLBF 0.5%	2.64	3.06
GLBF 0.75%	2.88	3.25
GLBF 1%	3.04	3.54

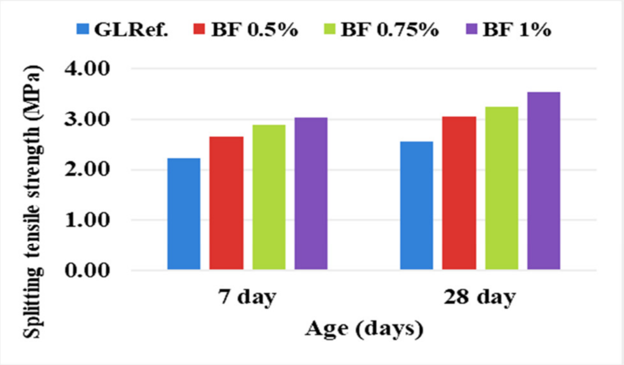

Fig. 4. Splitting tensile strength of geopolymer lightweight concrete with different basalt fiber content at different ages.

C. Flexural Strength

Table IX presents the results of the flexural tests conducted on geopolymer lightweight concrete. The flexural strength values increased as the basalt fiber content in the specimens increased. Enhancing the flexural strength is one of the primary functions of fiber reinforcement [40]. The flexural strength of geopolymer lightweight concrete also increased with the curing age, as illustrated in Figure 5. The results show that the flexural strength improved with basalt fiber content increases of 24.37%, 33.43%, and 40.09% at 7 days, and 21.6%, 32.14%, and 42.73% at 28 days, respectively.

TABLE IX. FLEXURAL STRENGTH RESULTS FOR 7 AND 28 DAYS

Mix	Flexural strength 7 days	Flexural strength 28 days
GL	2.79	3.3
GLBF 0.5%	3.48	4.01
GLBF 0.75%	3.73	4.36
GLBF 1%	3.94	4.71

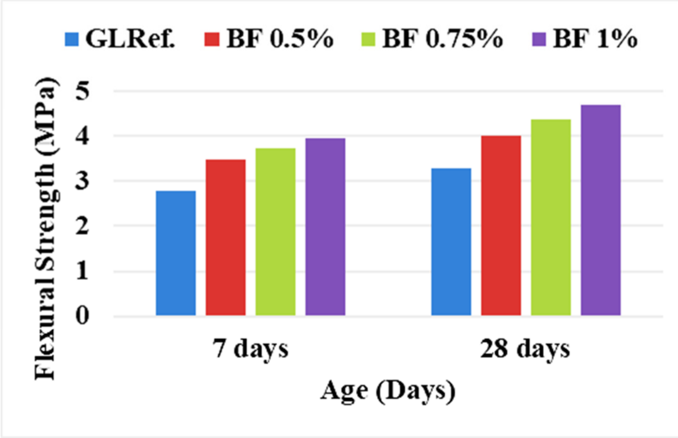

Fig. 5. Flexural strength of geopolymer lightweight concrete with different basalt fiber content at different ages.

VI. CONCLUSIONS

The goal of this work is to improve the mechanical properties of geopolymer lightweight concrete, which is typically brittle and requires a careful mix design. Basalt fiber was incorporated into the mixture in varying amounts (0.5%, 0.75%, and 1%) to evaluate its effect on strength development. The results showed that the inclusion of basalt fiber enhanced all measured mechanical properties. The compressive strength increased by 9.44%, 13.77%, and 16.53% at 7 days, and by 11.67%, 14.85%, and 17.5% at 28 days, for 0.5%, 0.75%, and 1% fiber content, respectively. Similarly, the splitting tensile strength improved by 18.57%, 29.28%, and 36.43% at 7 days, and by 20%, 27.5%, and 38.75% at 28 days. The flexural strength also increased by 24.37%, 33.43%, and 40.09% at 7 days, and by 21.6%, 32.14%, and 42.73% at 28 days, respectively.

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