iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** III **Month of publication:** March 2026

DOI: https://doi.org/10.22214/ijraset.2026.78314

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue III Mar 2026- Available at www.ijraset.com

Effect of Glass Fiber on the Properties of Geopolymer Concrete

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***Abstract:** Geopolymer concrete is produced by the reaction of alumino-silicate materials such as fly ash with alkaline activator solutions like sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The present study focuses on the strength and durability performance of fly ash-based geopolymer concrete with the addition of glass fibers.In this study, the alkaline solution to fly ash ratio was maintained at 0.5 and the sodium hydroxide solution concentration was taken as 10M. Glass fibers were added in different proportions to determine the optimum dosage. The compressive, split tensile, and flexural strengths of geopolymer concrete with glass fiber were evaluated as per relevant IS codes. The results showed that the compressive strength increased from 34.02 MPa to 38.08 MPa and the split tensile strength increased from 2.48 MPa to 3.1 MPa with the addition of glass fibers. Similarly, the flexural strength also improved compared to conventional geopolymer concrete. The study concluded that 1% glass fiber is the optimum dosage for enhancing the mechanical properties of geopolymer concrete.*

***Keywords:** Geo polymer, fly ash, workability, mechanical properties and durability properties.*

I. INTRODUCTION

Geopolymers are a class of inorganic polymer materials formed through the chemical reaction between aluminosilicate source materials and alkaline activator solutions. According to Cheng and Chiu (2003), geopolymers differ from conventional organic polymers because they are synthesized at relatively low temperatures and exhibit excellent properties such as non-combustibility, high heat resistance, and resistance to fire and acids. The production of geopolymers mainly involves three essential components: aluminosilicate source materials such as fly ash (FA), ground granulated blast furnace slag (GGBS), and metakaolin (MK); inert fillers such as sand and coarse aggregates; and alkaline activator solutions typically consisting of sodium hydroxide (NaOH) or potassium hydroxide (KOH) combined with sodium silicate (Na_2SiO_3). The geopolymerization process occurs in two main stages: dissolution of aluminosilicate materials in an alkaline environment, releasing silica and alumina, followed by polycondensation that forms a three-dimensional polymeric network structure.

Xu and Van Deventer (2000) reported that the rate of dissolution of aluminosilicate materials significantly affects the compressive strength of geopolymer products. Parameters such as calcium oxide (CaO) content, potassium oxide (K_2O) content, Si/Al ratio, type of alkaline activator, and curing conditions strongly influence the mechanical properties of geopolymer materials. The geopolymerization process generally follows a sol–gel mechanism in which aluminosilicate particles dissolve in alkaline silicate solutions and gradually form a hardened gel matrix. Various industrial by-products such as fly ash, blast furnace slag, red mud, and waste glass have been widely used as geopolymer source materials. Studies by Davidovits (1991, 1999), Palomo and Glasser (1992), and Rahier et al. (1996) confirmed that metakaolin and similar aluminosilicate materials effectively participate in geopolymerization reactions. Research has also demonstrated that curing temperature and duration play important roles in strength development. Van Jaarsveld, Van Deventer, and Lukey (2002) observed that curing geopolymer specimens at about 70°C for 24 hours significantly improved compressive strength. Palomo et al. (1999) further reported that a combination of sodium hydroxide and sodium silicate solutions produces higher compressive strength compared with using hydroxide solution alone because soluble silicates accelerate geopolymerization. Experimental studies by researchers such as Anurag Mishra (2008) and Chindaprasirt (2006) showed that geopolymer concrete can achieve compressive strengths ranging from 46 MPa to 70 MPa depending on the activator concentration and curing conditions. In structural applications, geopolymer concrete behaves similarly to conventional Portland cement concrete. Hardjito et al. (2004) reported that geopolymer paste effectively binds aggregates, allowing conventional concrete production techniques to be used. Aggregates constitute nearly 75–80% of the mass of geopolymer concrete. Studies by Sumajouw and Rangan (2006) on reinforced geopolymer concrete beams and columns revealed that their structural behavior and failure modes are comparable to those of reinforced cement concrete members.

Geopolymer concrete also exhibits excellent durability properties. Bakharev (2003) reported superior resistance to sulphate attack in alkali-activated slag concrete compared to ordinary Portland cement concrete. Song (2005) observed that geopolymer concrete exposed to sulphuric acid experienced minimal mass loss. Additionally, geopolymer materials demonstrate high fire resistance and corrosion protection for embedded steel reinforcement. Due to these advantages and their ability to reduce carbon dioxide emissions by utilizing industrial by-products such as fly ash and slag, geopolymer concrete has emerged as a sustainable alternative to conventional Portland cement concrete. However, standardized mix design procedures for geopolymer concrete are still under development, and most current designs rely on experimental trial-and-error methods.

II. MATERIALS AND THEIR PROPERTIES

A. Dalmia Cement (OPC)

Dalmia Ordinary Portland Cement (OPC) was used in this study as a binding material in concrete. It provides good strength, durability, and bonding properties in construction works. The physical properties such as fineness, consistency, setting time, and compressive strength were tested as per IS 4031 (Methods of Physical Tests for Hydraulic Cement). The specification for OPC cement is given in IS 8112:2013 (43 Grade OPC).

B. Fly Ash (Class C and Class F)

The fly ash used in this study was obtained from the Neyveli Thermal Power Plant, and it belongs to Class C grade. Fly ash is an important material required for the preparation of Geopolymer Concrete (GPC). It is obtained as a by-product from coal combustion in thermal power plants and during certain industrial processes. Fly ash is generally classified into two types: Class F and Class C, based on its chemical composition and source. In this project, Class C fly ash was used for the preparation of geopolymer concrete. The physical properties of fly ash were determined according to IS: 1727–1967, and the results are presented in **Table 1**

Table:1 Properties of fly ash

SI .No	Properties	Test results
1	Type	C
2	color	Brownish black
3	Specific gravity	2.28
4	consistency	38%

Table:2 Chemical Composition of class C and class F fly ash

Chemical Composition	Class C (%)	Class F (%)
SiO2	59.70	50
Al2O3	28.36	28.25
Fe2O3	4.57	13.5
CaO	2.10	1.78
MgO	0.83	0.89
SO3	0.40	0.38
Na2O	0.04	0.32
K2O	-	0.46
TIO2	1.82	-
Others	2.14	-
LOI	1.06	1.64

C. Fine Aggregate

Locally available sand passing through the 4.75 mm sieve was used in this experimental work as fine aggregate. Fine aggregate plays an important role in improving the workability and strength of concrete. The sand used was clean and free from impurities such as clay, silt, and organic matter. The physical properties of fine aggregates were determined in accordance with IS: 2386–1963, and the results are presented in Table 3

Table:3 Properties of fine aggregate

SI .No	**Properties**	**Test results**
1	Fineness modulus	3.34
2	Size of aggregate	4.75 mm passing
3	Specific gravity	2.57
4	Water absorption	0.64%
5	Bulk density	1710 kg/m3
6	Zone	II

D. Coarse Aggregate

Coarse aggregate used in concrete generally consists of crushed stone or granite with sizes ranging from 10 mm to 20 mm. It provides strength and stability to the concrete structure. Tests such as specific gravity, water absorption, and aggregate impact value were conducted as per IS 2386 (Part I–VIII):1963. The grading and quality requirements are specified in IS 383:2016.

Table :4 Properties of coarse aggregate

SI.No	Properties	Test results
1	Fineness modulus	9.16
2	Size of aggregate	20 mm
3	Specific gravity	2.94
4	Water absorption	0.4%
5	Bulk density	1472 kg/m3
6	Impact value	19%

E. Sodium Silicate Solution

Sodium silicate solution acts as an alkaline activator in geopolymer concrete and helps in the polymerization process. It improves the bonding and strength development of geopolymer concrete. The solution generally contains SiO_2, Na_2O, and water in suitable proportions. The properties and specifications of sodium silicate are generally referred from IS 381:1983 (Specification for Sodium Silicate).

Table: 5 Content of sodium silicate solution

SI.No	Composition	Values
1	SiO_2	14.7%
2	Na_2O	29.4%
3	water	55.9%

F. Sodium Hydroxide (NaOH)

Sodium hydroxide solution is used as an alkaline activator to dissolve silica and alumina from fly ash during geo polymerization. It is prepared by dissolving NaOH flakes or pellets in water to obtain the required molarity such as 8M, 10M, or 12M. The solution is prepared at least 24 hours before mixing to ensure proper dissolution. The chemical quality of sodium hydroxide is referred as per IS 252:2013 (Specification for Caustic Soda).

Table: 6 Content of sodium hydroxide

SI.NO	Description	Values
1	ASSAY NLT	98%
2	Impurities	0.01%
3	Water	1%

G. Properties of Glass Fiber

Glass fibers are made primarily of silicon oxide with small amounts of other oxides added to improve their properties. Glass fibers are characterized by high strength, good temperature resistance, corrosion resistance, and low cost, which makes them suitable for reinforcing concrete. In this study, alkali-resistant E-glass fibers were used with a length of 50 mm, nominal diameter of 0.014 mm, specific gravity of 2.6, and density of 2650 kg/m³. The properties of glass fiber used in this study are presented in Table 3.6.

Table: 7 Properties of glass fiber

SI.No	**Properties**	**Values**
1	Density(g/cm³)	2.6
2	Youngs modulus(Gpa)	87
3	Tensile strength(Gpa)	2.53
4	Tensile elongation(%)	2.9

H. Water

Water used in concrete mixing should be clean and free from harmful substances such as oils, acids, alkalis, and organic impurities. It is used for mixing and curing of concrete. The quality of water directly affects the strength and durability of concrete. The suitability of water for concrete is specified in IS 456:2000 (Plain and Reinforced Concrete Code of Practice)

III. MIXTURE PROPORTIONS

As in the case of Portland cement concrete, the coarse and fine aggregates occupy about 75 to 80% of the mass of geopolymer concrete. The performance criteria of a geopolymer concrete depend on the application. The compressive strength of hardened concrete and the workability of fresh concrete are selected as the performance criteria.

Rangan was proposed guidelines for the design of heat cured low calcium fly ash based geopolymer concrete. Based on the results obtained from numerous mixtures made in the laboratory over a period of four years the data in table 3.6 for the design of low calcium fly ash based geopolymer concrete were proposed. The above proposed method for the design of mixture proportion was adopted in this project work. The mixture proportions for alkaline liquid to fly ash ratio as 0.5 were given in table 8.

Table :8 Mixture proportion per m³ of geopolymer concrete with glass fiber

SI.NO	Ingredients	Quantity per m³
1	Alkaline liquid to fly ash ratio	0.5
2	Sodium silicate solution	160.72 kg/m³
3	Sodium hydroxide solution	64.28 kg/m³
4	Fly ash	450 kg/m³
5	Fine aggregate	678 kg/m³
6	Coarse aggregate	924 kg/m³
7	Glass fiber	5 kg/m³

IV. MANUFACTURE OF GEOPOLYMER CONCRETE

Sodium hydroxide (NaOH) solution was prepared by dissolving NaOH flakes in water based on the required molarity. For example, a 10M NaOH solution required 400 g of NaOH solids per litre of solution, considering the molecular weight of NaOH as 40. The ratio of sodium hydroxide solution to sodium silicate solution was maintained as 2.5. Both solutions were mixed at least one day prior to casting to prepare the alkaline liquid. On the day of casting, the alkaline liquid was mixed with water to prepare the liquid component of the mixture. Glass fiber was added in proportions of 0.5%, 1%, 1.5%, and 2% to determine the optimum dosage based on compressive strength, split tensile strength, flexural strength, water absorption, and sulphate resistance tests. For the preparation of geopolymer concrete, fly ash and aggregates in saturated surface dry condition were first mixed thoroughly in a pan mixer. The alkaline solution was then added to the dry mix and mixed further to produce fresh concrete.

The concrete was immediately cast into cube moulds (100×100×100 mm), cylinder moulds (100×200 mm), and beam moulds (100×100×500 mm) in three layers with proper compaction using 25 manual strokes per layer. A total of 120 specimens were cast to study the influence of various parameters on strength and durability properties. After casting, the specimens were cured under ambient curing conditions.

V. METHODS

A. Workability test

The workability of fresh geopolymer concrete was determined using the conventional slump test as per IS: 1199 (1989). Workability refers to the ease with which fresh concrete can be mixed, placed, compacted, and finished without segregation. Before casting the concrete into moulds, the slump value was measured using a standard slump cone apparatus. In this study, the slump value of fresh geopolymer concrete was maintained within the range of 30 mm to 80 mm to ensure proper workability.

B. Compressive strength test

The compressive strength test of hardened fly ash-based geopolymer concrete was carried out using a compression testing machine (CTM) of 3000 kN capacity as per IS: 516-1959. A total of 30 cube specimens of size 100 mm × 100 mm × 100 mm were cast and tested at the ages of 7 days and 28 days. The compressive strength value reported for each mix was taken as the average of three specimens.

C. Split tensile strength test

The split tensile strength test was conducted to determine the indirect tensile strength of geopolymer concrete. Cylindrical specimens of 100 mm diameter and 200 mm height containing glass fibers were cast. After 24 hours, the specimens were demoulded and subjected to curing. After 28 days, the specimens were taken out, allowed to dry, and tested in a universal testing machine (UTM) by placing the cylinder horizontally under compressive loading.

D. Flexural strength test

The flexural strength test was carried out to determine the bending strength of geopolymer concrete. Beam specimens of size 100 mm × 100 mm × 500 mm were tested after 28 days of curing using a universal testing machine with a proving ring capacity of 5000 kg. The flexural strength corresponding to the failure load was calculated based on the mode of failure.

E. Water absorption test

Durability properties of geopolymer concrete were also studied. The water absorption test was conducted as per ASTM C1012 to evaluate the permeability characteristics of concrete. A total of 15 cube specimens (100 mm × 100 mm × 100 mm) were cast and tested after 56 days of curing. The reported water absorption value represents the average of three specimens.

F. Sulphate test

The sulphate resistance test was carried out according to ASTM C642 to study the resistance of geopolymer concrete against sulphate attack. For this test, 15 cube specimens of size 100 mm × 100 mm × 100 mm were prepared and tested at the age of 56 days. The sulphate attack results were calculated as the average value of three test specimens. These experimental tests were conducted to evaluate the mechanical and durability properties of fly ash-based geopolymer concrete containing glass fibers.

VI. RESULTS AND DISCUSSION

A. Compressive Strength

The compressive strength of geopolymer concrete with glass fiber cubes was tested at 7, 28 days of age after casting on standard compression testing machine as per IS: 516-1959. Each of the compressive strength test data corresponds to the mean value of the compressive strength of three test concrete cubes.

The compressive strength for geopolymer concrete on 28th day was 34.02 Mpa for 0%, 35.13 Mpa for 0.5%, 38.08 Mpa for 1%, 35.06 Mpa 1.5% and 30.5 Mpa for 2% addition of glass fiber in geopolymer concrete. It was found that the compressive strength increases upto 1% addition of glass fiber in geopolymer concrete.

Table 9: Compressive strength of geopolymer concrete with glass fiber

Time period	Conventional (mpa)	Fiber added (%)			
		0.5	1.0	1.5	2
7 days	19.90	21.50	24.03	24.98	18.20
28 days	34.02	35.13	38.08	35.06	30.50

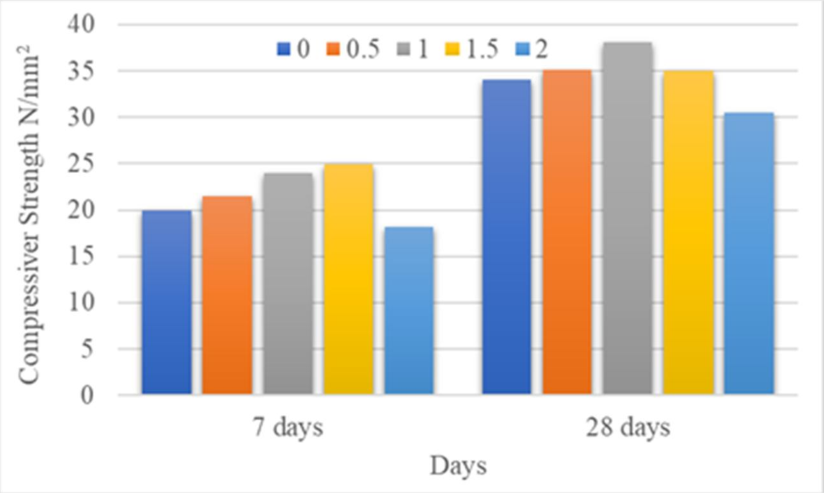

Fig 1 Compressive strength of geopolymer concrete with glass fiber at 28 days

Fig 2 Cube specimen under ambient curing

B. Split Tensile Strength

The split tensile strength of geopolymer concrete with glass fiber cylinders was tested at 28 days of age after casting on universal testing machine as per IS:4816-1980. Each of tensile strength test data corresponds to the mean value of the split tensile strength of three test concrete cylinders. The split tensile strength for geopolymer concrete on 28th day was 2.48 Mpa for 0%, 2.56 Mpa for 0.5%, 3.1 Mpa for 1%, 2.85 Mpa 1.5% and 2.36 Mpa for 2% addition of glass fiber in geopolymer concrete. It was found that the split tensile strength increases upto 1% addition of glass fiber in geopolymer concrete.

Table 10: Split tensile strength of geopolymer concrete with glass fiber

Time period	Conventional (mpa)	Fiber added (%)			
		0.5	1.0	1.5	2
28 days	2.48	2.56	3.10	2.85	2.36

Fig 3 Split tensile strength of geopolymer concrete with glass fiber at 28 days

Fig 4 Split tensile strength testing of cylinder specimen

C. *Flexural Strength*

The flexural strength of geopolymer concrete with glass fiber beam was tested at 28 days of age after casting on universal wood testing machine as per IS:516-1959. Each of flexural strength test data corresponds to the mean value of the flexural strength of three test concrete beams. The flexural strength for geopolymer concrete on 28th day was 3.27 Mpa for 0%, 5.29 Mpa for 0.5%, 3.1 Mpa for 1%, 5.76 Mpa 1.5% and 3.26 Mpa for 2% addition of glass fiber in geopolymer concrete. It was found that the flexural strength increases upto 1% addition of glass fiber in geopolymer concrete.

Table 11: Flexural strength of geopolymer concrete with glass fiber

Time period	Conventional (mpa)	Fiber added (%)			
		0.5	1.0	1.5	2
28 days	3.27	5.29	7.06	5.76	3.26

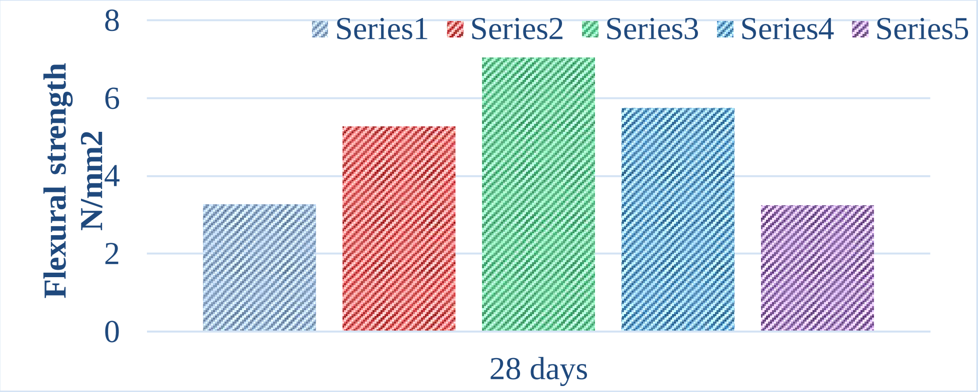

Fig 5 Flexural strength of geopolymer concrete with glass fiber at 28 days

Fig 6 Flexural strength testing of beam specimen

D. *Water Absorption test*

The water absorption test of geopolymer concrete with glass fiber cubes was tested at 56 days. The water absorption for Geopolymer concrete on 56th day was 2.4 for 0%, 3 for 0.5%, 3.2 for 1%, 4 for 1.5% and 4.2 for 2% addition of glass fiber in geopolymer concrete. Water absorption was found to be between 2.4 – 4.2. It was found that, there is an increase in water obsorption with the increase in addition of fiber in geopolymer concrete.

Table 12 Water Absorption Test

Fiber added (%)	Dry weight(kg)	Wet weight(kg)	Water absorption (%)
0	2.177	2.231	2.4
0.5	2.313	2.383	3.0
1.0	2.184	2.254	3.2
1.5	2.204	2.293	4.0
2.0	2.296	2.396	4.2

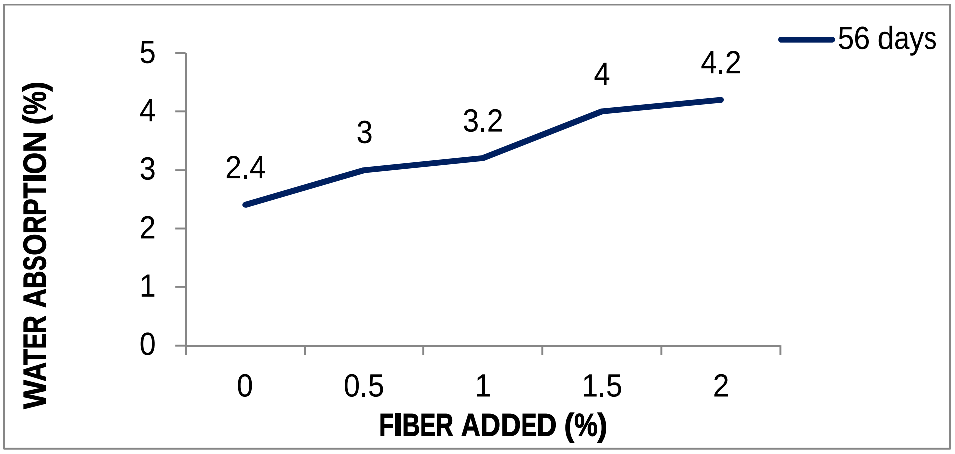

Fig 7 Water absorption of geopolymer concrete with glass fiber at 56 days

Fig 8 Water Absorption Test

E. Sulphate test

The sulphate test of geopolymer concrete with glass fiber cubes was tested at 56 days. The Compressive strength for sulphate test Geopolymer concrete on 56th day was 4.62 for 0%, 8.02 for 0.5%, 8.34 for 1%, 9.52 for 1.5% and 10.2 for 2% addition of glass fiber in geopolymer concrete.

Weight loss in geopolymer concrete was tested on 56th day was 8.42 for 0%, 4.3 for 0.5%, 1.5 for 1%, 1.8 for 1.5% and 3.7 for 2% addition of glass fiber in geopolymer concrete. The weight loss decreases with the increase in addition of glass fiber upto to 1.5% in geopolymer concrete. From the results it was found that weight loss was maximum in plain geopolymer concrete when compared with glass fiber reinforced geopolymer concrete upto to an addition of glass fiber, when tested for sulphate attack.

Table 13: Sulphate test

Fiber added (%)	Dry weight (kg)	Wet weight (kg)	Weight loss (%)	Compressive strength (mpa)
0	2.177	1.994	8.4	4.62
0.5	2.313	2.212	4.3	8.02
1.0	2.184	2.150	1.5	8.34
1.5	2.204	2.164	1.8	9.52
2.0	2.296	2.211	3.7	10.2

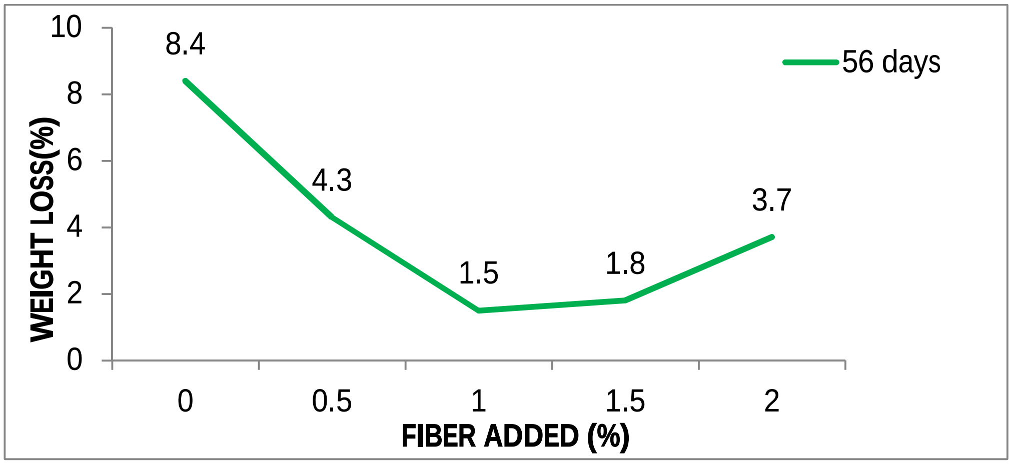

Fig 9 Sulphate test (weight loss) of geopolymer concrete with glass fiber at 56 days

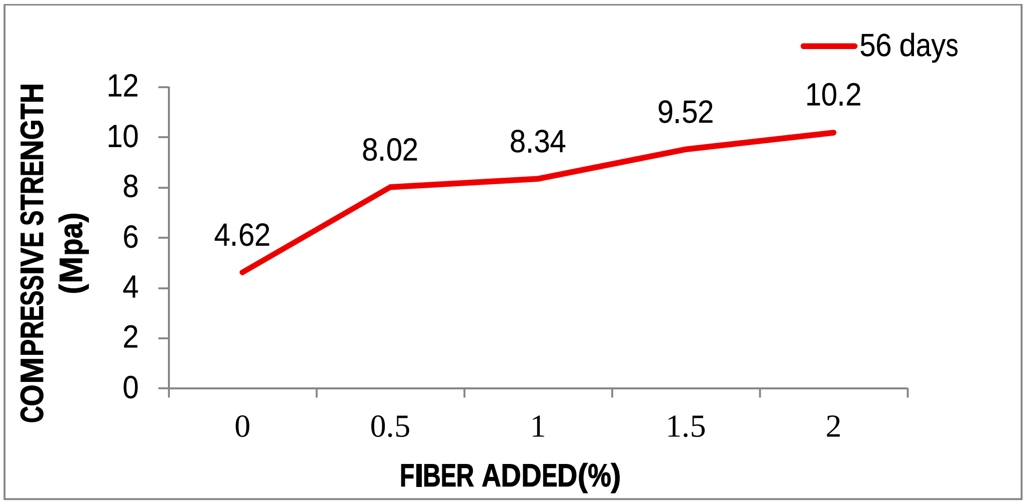

Fig 10 Sulphate test (Compressive loss) of geopolymer concrete with glass fiber at 56 days

Fig 10 Sulphate Test

VII. CONCLUSIONS

The results of the study show that the alkaline solution to fly ash ratio and the concentration of sodium hydroxide significantly influence the compressive strength development of geopolymer concrete. An alkaline solution to fly ash ratio of 0.5 with 10M NaOH produced higher compressive strength when glass fibers were added. The curing condition also played an important role in the strength development of geopolymer concrete. The compressive strength of glass fiber reinforced geopolymer concrete ranged from 34.02 MPa to 38.08 MPa at 28 days, and the addition of 1% glass fiber increased the compressive strength by about 10% compared to conventional geopolymer concrete. Similarly, the split tensile strength varied from 2.48 MPa to 3.1 MPa, showing an increase of about 10%, while the flexural strength ranged from 3.27 MPa to 7.06 MPa, with an improvement of about 20% for 1% glass fiber addition. The results indicate that 1% glass fiber is the optimum dosage for improving the mechanical properties of geopolymer concrete. The water absorption of geopolymer concrete was found to be between 2.4% and 4.2%, and it slightly increased with the addition of glass fibers. However, the weight loss due to sulphate attack decreased with the increase in glass fiber content up to 1.5%, indicating improved durability. Overall, geopolymer concrete with 1% glass fiber reinforcement showed better strength and durability and can be effectively used in aggressive environmental conditions. Moreover, the use of Class C fly ash in geopolymer concrete helps reduce the consumption of Portland cement and indirectly lowers the emission of greenhouse gases such as CO_2, making it an environmentally friendly construction material.

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