Evaluation Of Hybrid Fiber Reinforced Geopolymer Concrete

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***Abstract*—The growing demand for sustainable construction materials has led to the development of geopolymer concrete (GPC) as an eco-friendly alternative to conventional Portland cement concrete. This study investigates the performance of Hybrid Fiber Reinforced Geopolymer Concrete (HFRGC) incorporating a combination of steel, polypropylene, glass, and flax fibers. The geopolymer matrix was formulated using industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS), activated with alkaline solutions.**

The primary objective of this research is to evaluate the mechanical properties of HFRGC, particularly compressive strength, split tensile strength, and flexural strength, under ambient curing conditions. An M20 grade mix was developed through trial mix optimization, and specimens including cubes, cylinders, and beams were prepared, cured for 28 days, and tested.

The study confirms that ambient-cured HFRGC is a viable and sustainable construction material with improved mechanical properties. The findings contribute to addressing existing research gaps related to multi-fiber hybridization and provide a foundation for further studies on durability and standardization of geopolymer composites.

I. INTRODUCTION

Geopolymer concrete (GPC) is an environmentally friendly alternative to conventional concrete that reduces carbon emissions by replacing cement with industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS). However, GPC exhibits brittle behavior and low resistance to cracking. To address these limitations, this study focuses on the development of hybrid fiber reinforced geopolymer concrete (HFRGC) using steel, polypropylene, glass, and flax fibers.

The objective is to achieve M20 grade concrete under ambient curing conditions while improving mechanical performance and crack resistance.

- To develop hybrid fiber reinforced geopolymer concrete using fly ash and GGBS.
- To evaluate compressive, split tensile, and flexural strength.

Farhan et al. (2023) investigated the durability of polypropylene fiber-reinforced GGBFS-based alkali-activated composites under suphate attack and freeze–thaw cycles. The study aimed to assess how the addition of polypropylene fibers influences the resistance of geopolymer materials to aggressive environmental conditions

Moujoud et al. (2023) conducted a comprehensive review of geopolymer composites reinforced with natural fibers, focusing on recent advances in processing techniques and resulting material properties

II. MATERIAL

The performance of geopolymer concrete depends significantly on the properties of its constituent materials. The materials used in this study are described below:

1. Fly Ash (Class F)
Fly ash is a by-product of coal combustion in thermal power plants. It is rich in silica and alumina, which are essential for geopolymerisation.

2. Ground Granulated Blast Furnace Slag (GGBS)
GGBS is obtained from the rapid cooling of molten slag from steel manufacturing. It enhances early

strength development, reduces permeability, and improves durability.

3. Fine Aggregate
Manufactured sand (M-sand) conforming to Zone II of IS 383 was used as fine aggregate.

4. Coarse Aggregate
Crushed granite aggregate of 20 mm size was used. It provides strength and stability to the concrete.

5. Steel Fibers
Steel fibers act as primary reinforcement in the mix. They improve tensile strength, flexural strength, and toughness.

6. Polypropylene Fibers
Polypropylene fibers are synthetic fibers that help in controlling plastic shrinkage cracks.

7. Glass Fibers
Alkali-resistant glass fibers improve tensile and flexural strength.

8. Flax Fibers
Flax fibers are natural, eco-friendly fibers with good tensile strength.

9. Alkaline Activator Solution
The activator solution consists of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3).

10. Water
Potable water was used for preparing the mix. It ensures proper reaction and workability.

III. MATERIAL PROPERTIES

The characteristics of different components of the ternary blend hybrid fibre reinforced GPC mix is discussed below.

1. Class F fly ash
Fly ash (FA) is a byproduct of burning of coal, comprising particles that are expelled from boilers powered by coal alongside flue gases. Class F fly ash from the Tuticorin thermal power station was employed in the study. Class F fly ash is of exceptional quality for the creation of geopolymer concrete since it includes less than 10% CaO and 5% Carbon.

2. Ground granulated blast furnace slag
Molten iron slag, a byproduct created during the manufacture of iron and steel in thermal industries, is cooled to produce ground granulated blast furnace slag (GGBS). A glassy and granular substance known as GGBS is created when the molten slag is quickly introduced with water or steam.

Table 1. Properties of Fly ash and GGBS

Properties	Fly ash	GGBS
Specific gravity (gm/cc)	2	2.47
Colour	Dark grey	Off white

3. Fine and Coarse Aggregate
The aggregate underwent several tests, including sieve analysis according to IS 3832016, evaluation of specific gravity based on IS 2386 (Part III) 1963 (Reaffirmed 2002), measurement of bulk density, calculation of fineness modulus, and evaluation of water absorption.

1) Fine aggregate
Considering the environmental factors and shortage of good quality river sand, manufactured sand was used for the entire work. The physical characteristics of the material were assessed through laboratory tests. Fine aggregate, in the form of manufactured sand that passed through a 4.75 mm sieve and met the specifications for Zone II grade, was employed.

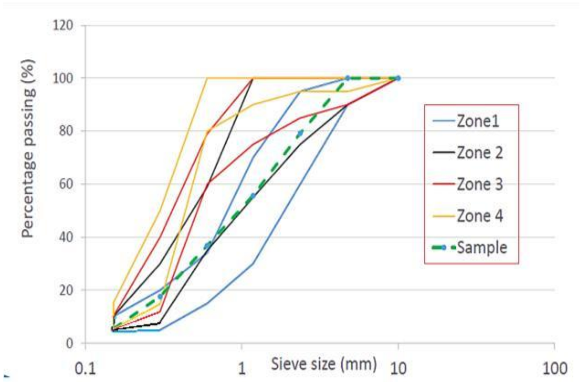


Fig 1. Grading curve of fine aggregate

Table 2. Properties of fine aggregates

Material Properties	Test Results
Specific gravity	2.58
Sieve analysis	Conforming to Zone II as per IS 383- 2016
Water absorption	4.21%
Bulk density	1.89 x 10^3 kg/m^3
Fineness modulus	3.10

2)Coarse aggregate

The physical characteristics of the crushed coarse aggregates, with a nominal size of 20 mm, were evaluated using laboratory tests in accordance with the specifications outlined in IS standards.

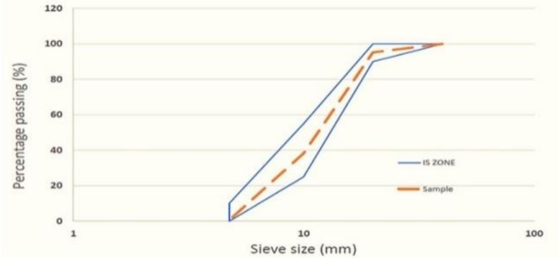


Fig 2. Grading curve of coarse aggregate

Table 3. Properties of coarse aggregates

Material Properties	Test Results
Specific gravity	2.82
Sieve analysis	Conforming to IS 383- 2016
Water absorption	1%
Bulk density	1.83 x 10^3 kg/m^3
Fineness modulus	7.45

4. Glass fibre

Glass fibre (GF) has the ability to significantly enhance the mechanical properties and ductility of concrete. In geopolymer concrete (GPC), glass fibre serves as a dispersed micro-reinforcement matrix, aiding in the restriction of crack propagation and improving both the flexural and splitting tensile strength of the structure.

Table 4. Physical properties of glass fibre (Source: provided by supplier)

Parameter	Value
Fiber type	Alkali-Resistant (AR)
Specific gravity	2.68 gm/cc
Filament diameter	14 µm
Cut length	12 mm
Tensile strength	1700 MPa
Modulus of elasticity	72 GPa

5. Steel fibre

Crimped steel fibres are the metallic fibres used in this experimental investigation to provide fibre reinforcement. The density of the steel fibres (SF) used in this study is 7810 kg/m3.

Table 5. Properties of steel fibres (Source: provided by manufacturer)

Parameter	Value
Type	Crimped steel fibre
Aspect ratio	60
Diameter	0.50 mm
Length	30 mm
Tensile strength	1196 MPa
Classification	Type I, cold drawn wire and Type V modified cold drawn wire

6. Polypropylene fibre

The properties of the polypropylene fibre (PPF) are given in Table A.6. Polypropylene fibers with aspect ratio 307.69 was used.

Table 6. Properties of Polypropylene fibre (Source: provided by manufacturer)

Parameter	Value
Specific gravity	0.91 g/cc
Constituents	Virgin Polypropylene C3H6
Type	Fibrillated
Fibre thickness	39 micrometres
Fibre length	12 mm
Young's modulus	5500-7000 MPa
Tensile strength	350 MPa
Melting point	160^{o}C

7. Alkaline activators

Sodium silicate solution and sodium hydroxide solution make up the alkaline activator for the investigation. 99 percent pure sodium flakes were dissolved in water to create the sodium hydroxide solution (SHS). The research makes use of sodium silicate solution (SSS), a commercial product with a weight ratio (SiO_2/Na_2O) of two.

8. Water

This experimental study utilized the potable water supplied by the college's water system.

IV. METHODOLOGY

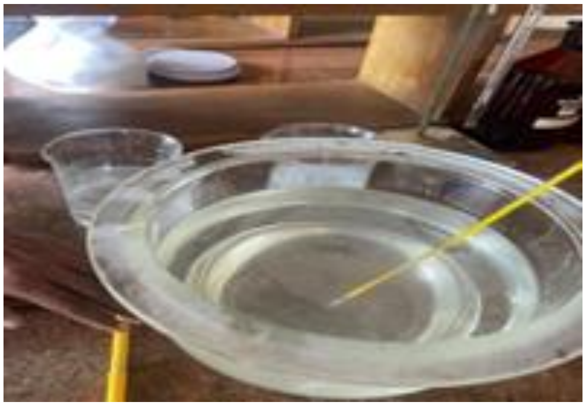
The methodology adopted in this study involves a systematic experimental procedure to develop and evaluate hybrid fiber reinforced geopolymer concrete.

1. Material Procurement and Preparation

All materials including fly ash, GGBS, aggregates, fibers, and alkaline activators were collected and tested to ensure they meet required standards. Flax fibers were chemically treated with 5% NaOH solution to improve their resistance to the alkaline environment.

2. Preparation of Alkaline Activator Solution

The alkaline activator was prepared 24 hours before mixing. Sodium hydroxide pellets were dissolved in water to obtain a 12M solution. After cooling, it was mixed with sodium silicate in a ratio of 1:2.5 to form a homogeneous solution.



3. Mix Design

A trial-and-error method was adopted to achieve the desired M20 grade concrete. Different mixes were prepared with varying ratios of fly ash and GGBS (70:30 to 50:50) and fiber content (1.0% to 1.3%). Based on trial results, the optimal mix proportion was selected.

4. Mixing Process

- Dry materials (fly ash, GGBS, fine and coarse aggregates) were mixed thoroughly.
- Hybrid fibers were added gradually to ensure uniform distribution and prevent balling.
- The alkaline activator solution was then added and mixed until a uniform and workable mix was obtained.

5. Casting of Specimens

Concrete was poured into standard molds:

- Cubes (150×150×150 mm) for compressive strength
- Cylinders (150×300 mm) for split tensile strength
- Beams (100×100×500 mm) for flexural strength

Each mold was filled in layers and compacted using a vibrating table to remove air voids.

6. Demoulding

After 24 hours, the specimens were removed from molds and labeled properly for identification.

7. Curing

Specimens were cured under ambient conditions (27–30°C) for 28 days. Unlike conventional concrete, no heat curing was used, making the process practical for real construction conditions.

8. Testing of Specimens

After curing, specimens were tested using a Universal Testing Machine:

- Compressive strength test on cubes
- Split tensile strength test on cylinders
- Flexural strength test on beams

The average of three specimens was taken for accuracy.

9. Analysis of Results

The results were compared with plain geopolymer concrete. Crack patterns and failure modes were observed to evaluate the effectiveness of hybrid fbers.

V. RESULT

Four trial mixes were prepared with varying FA/GGBS ratios and fiber volume fractions. The mixes were tested for compressive strength at 7 days to evaluate their performance. The results are presented in Table 4.1 and Fig. 4.1.

Table 9. Trial mix compressive strength results

Trial Mix	FA: GGBS Ratio	Fiber Content (%)	7-Day Compressive Strength (MPa)
Trial Mix 1	70:30	1.0	18.2
Trial Mix 2	65:35	1.1	20.5
Trial Mix 3	60:40	1.2	22.8
Trial Mix 4	50:50	1.3	24.8

Trial Mix 4, with a FA:GGBS ratio of 50:50 and total fiber content of 1.3%, exhibited the highest 7-day compressive strength of 24.8 MPa. This mix was selected as the final optimized mix for achieving M20 grade concrete after 28 days of ambient curing.

5.1. Mechanical Properties of Optimized Mix

After 28 days of ambient curing, the optimized mix (Trial Mix 4) was tested for compressive, split tensile, and flexural strengths. A control mix (plain GPC without fibers) was also tested for comparison. The results are presented in Table 4.2.

Table 10. Mechanical properties of final mix vs. control

Property	Plain GPC (Control)	HFRGC (Optimized Mix)	Improvement (%)
Compressive Strength (MPa)	24.8	28.86	+16.4%
Split Tensile Strength (MPa)	2.50	2.61	+4.4%
Flexural Strength (MPa)	4.64	5.86	+26.3%

5.2. Comparison with Plain GPC

The results demonstrate that the hybrid fiber reinforced geopolymer concrete exhibited significant improvements in mechanical properties compared to plain GPC:

- Compressive Strength:

Increased by 16.4% from 24.8 MPa to 28.86 MPa, confirming that the optimized mix achieved the target M20 grade under ambient curing conditions.

- Flexural Strength:

Increased by 26.3% from 4.64 MPa to 5.86 MPa, representing the most significant improvement among the tested properties. This substantial increase is attributed to the synergistic effect of the hybrid fibers, particularly steel fibers, which provide effective crack bridging and load transfer across the flexural tension zone.

- Split Tensile Strength:

Increased by 4.4% from 2.50 MPa to 2.61 MPa. While this improvement is more modest, it indicates that the hybrid fiber system contributes to enhanced tensile capacity, primarily through the polypropylene and glass fibers that control microcrack formation.

The modest improvement in split tensile strength compared to flexural strength can be attributed to the random distribution of fibers and the orientation effect. In flexural testing, fibers align favorably with the tensile stress direction, whereas in split tensile testing, the stress distribution is more complex and fibers may not align optimally with the principal tensile stresses.

5.3. Crack Pattern Analysis

Visual observation of the tested specimens revealed distinct differences in crack patterns between the plain GPC and HFRGC specimens:

- Plain GPC:

Exhibited brittle failure with a single dominant crack propagating rapidly across the specimen. No secondary cracking was observed, and the specimens separated completely upon reaching peak load.

- HFRGC:

Demonstrated ductile failure with multiple fine cracks distributed throughout the specimen. The hybrid fibers effectively bridged the cracks, preventing their propagation and allowing the specimen to sustain load even after initial cracking. The post-cracking load-bearing capacity was significantly enhanced, indicating improved toughness and energy absorption.

Crack pattern observation in hybrid fiber mix

The enhanced crack-bridging behavior observed in the hybrid fiber mix confirms the synergistic effect of the four-fiber system. Steel fibers contributed to macro-crack control and post-cracking ductility, while polypropylene and glass fibers controlled micro-cracks at early stages. Flax fibers, despite being natural, provided additional crack control and contributed to the overall sustainability of the composite.

VI. CONCLUSION

The study successfully developed a hybrid fiber reinforced geopolymer concrete using a combination of steel, polypropylene, glass, and flax fibers. The use of fly ash and GGBS as binder materials significantly reduced the dependence on cement, making the concrete more sustainable and environmentally friendly.The optimized mix achieved the target M20 grade under ambient curing conditions, proving that heat curing is not necessary for achieving adequate strength. The incorporation of hybrid fibers resulted in noticeable improvements in mechanical properties. Among these, flexural strength showed the highest improvement due to the effective crack-bridging mechanism of fibers. Compressive strength also improved, while split tensile strength showed moderate enhancement.

The crack pattern analysis revealed that plain geopolymer concrete exhibited brittle failure, whereas hybrid fiber reinforced concrete showed ductile behavior with multiple fine cracks. This indicates improved toughness and energy absorption capacity.The synergistic action of different fibers played a key role in enhancing performance. Steel fibers controlled macro-cracks, polypropylene and glass fibers controlled micro-cracks, and flax fibers contributed to sustainability and additional crack resistance.

Overall, the study demonstrates that hybrid fiber reinforced geopolymer concrete is a viable and sustainable alternative for conventional concrete. It is especially suitable for general construction applications where ambient curing is required. The results also highlight the potential of using natural fibers along with synthetic fibers to achieve both performance and sustainability.

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