Influence of Steel Fiber Content on the Tensile Properties of M50 Grade Geopolymer Concrete

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ABSTRACT

Geopolymer concrete (GPC) is gaining prominence as an eco-friendly alternative to ordinary Portland cement (OPC) concrete, offering advantages such as reduced carbon emissions, enhanced durability, and superior resistance to chemical attack. However, its inherently brittle nature and low tensile strength limit its use in structural applications where tensile performance is critical. This study investigates the effect of incorporating steel fibers on the tensile behaviour of M50 grade geopolymer concrete. The mix design utilized fly ash and ground granulated blast furnace slag (GGBS) as binder materials, activated by a combination of sodium hydroxide and sodium silicate solutions. Four different fiber volume fractions - 0%, 0.5%, 1.0%, and 1.5% were introduced into the GPC matrix, and specimens were subjected to compressive, split tensile, flexural, and strut-and-tie tests to evaluate mechanical performance. The results indicate that the addition of steel fibers significantly enhances the tensile strength, ductility, and post-cracking behaviour of the concrete. Among the tested dosages, 1.0% fiber content was found to be optimal, providing a balanced improvement in strength and workability. This research also establishes correlations between different tensile testing methods, contributing to a comprehensive understanding of fiber-reinforced geopolymer concrete under various loading conditions.

Keywords: Geopolymer concrete, Steel fibers, Tensile strength, Split tensile test, Flexural behaviour, Fiber-reinforced concrete, M50 grade, Strut-and-tie

1. INTRODUCTION

The increasing environmental impact of cement production has driven the search for alternative, sustainable construction materials. Ordinary Portland Cement (OPC), the main binder in conventional concrete, is associated with approximately 8% of global CO_2 emissions, largely due to the calcination of limestone and high energy consumption during manufacturing [1]. In response, Geopolymer Concrete (GPC) has emerged as an eco-friendly alternative that utilizes industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS) to form an aluminosilicate-based binder through a geopolymerization reaction activated by alkaline solutions [2], [3].

GPC offers several advantages over OPC-based concrete, including higher compressive strength, improved resistance to acid and sulphate attack, lower shrinkage, better fire resistance, and a significantly reduced carbon footprint [4], [5]. However, a major limitation of GPC lies in its brittle nature and inherently low tensile strength, which restricts its application in structural elements subjected to tension, such as beams and slabs. Improving the tensile behaviour of GPC is, therefore, essential to broaden its usage in load-bearing and flexural members [6].

Fiber reinforcement has been recognized as an effective method to enhance the tensile, flexural, and post-cracking performance of concrete. Among the various types of fibers such as polypropylene, glass, basalt, and carbon steel fibers have been widely studied for their ability to improve crack resistance, energy absorption, and toughness due to their high modulus of elasticity and tensile strength [7], [8]. Previous research has shown that steel fibers significantly enhance tensile and flexural properties in both OPC and geopolymer matrices [9], although the optimal dosage and interaction mechanisms in high-strength GPC remain an area of ongoing investigation.

While several studies have focused on fiber-reinforced GPC, there is limited research specifically targeting M50 grade geopolymer concrete with varying steel fiber dosages under multiple tensile test conditions. Additionally, comprehensive comparisons between tensile strength results from different testing methods—such as split tensile, flexural, and strut-and-tie tests—are still lacking.

2. Literature Review

A.M. Shende et al. (2012) conducted an experimental study on M40 grade concrete with varying dosages of steel fibers (0%, 1%, 2%, and 3%). Their investigation revealed that increasing the steel fiber content significantly improved compressive, split tensile, and flexural strengths. The enhancement in mechanical performance was attributed to improved crack resistance and fiber bridging effects. They also noted that an optimum dosage existed beyond which workability was negatively impacted.

J. Thomas and A. Ramaswamy (2007) analyzed the mechanical properties of steel fiber-reinforced concrete across three different grades of strength (35 MPa, 65 MPa, and 85 MPa). Their results demonstrated that steel fibers had a marginal effect on compressive strength but significantly improved tensile and flexural strength. Using regression models, they introduced a "reinforcement index" to quantify the interaction between fiber dosage and matrix strength, which contributed to a better understanding of post-cracking behaviour.

P.S. Song and S. Hwang (2004) focused on high-strength concrete reinforced with hooked-end steel fibers at different volume fractions (0.5% to 2.0%). Their study found that the splitting tensile strength improved by up to 98% and flexural strength by over 120% at higher fiber contents. They also developed predictive models for mechanical behaviour and reported substantial improvements in ductility and energy absorption capacity.

Zuzana Marcalikova et al. (2020) compared two types of steel fibers—straight and double-hooked—at different dosages (40, 75, and 110 kg/m³). Their experimental work demonstrated that hooked-end fibers significantly outperformed straight fibers in both split tensile and flexural strength. However, the researchers also observed that increasing fiber dosage beyond a certain limit led to a reduction in compressive strength due to poor dispersion and balling of fiber.

V. Keerthy and Y. Himath Kumar (2017) studied geopolymer concrete made with GGBS and fly ash, using sodium hydroxide and sodium silicate as activators. Although their study did not include fibers, they established the mechanical viability of GPC under ambient curing conditions and laid a foundation for further exploration of reinforced geopolymer systems.

K. Lakshmi and M. Sai Narasimha Rao (2019) investigated the incorporation of glass fibers in GPC and found that tensile strength improved up to a fiber volume fraction of 3%. This study reinforced the potential of fiber-reinforced geopolymer concrete (FRGPC) but highlighted the need for comparative analysis using other fiber types, such as steel.

3. Materials and Methods

3.1 Materials Used

The materials used in this study were selected based on their suitability for geopolymer concrete and their availability. The mix was designed for **M50 grade geopolymer concrete**, incorporating both conventional and alternative materials, with the addition of steel fibers at various dosages.

1. **Binder Materials**:
   a. **Fly Ash (Class F):** a low-calcium fly ash obtained from thermal power plants, serving as the primary aluminosilicate source.
   b. **Ground Granulated Blast Furnace Slag (GGBS)**: incorporated to improve early strength and allow ambient curing.
2. **Alkaline Activators**:
   a. **Sodium Hydroxide (NaOH):** prepared in 12M concentration, dissolved 24 hours in advance to stabilize exothermic reaction.
   b. **Sodium Silicate (Na_2SiO_3)**: used in combination with NaOH in a 2.5:1 ratio by weight, supplying soluble silica for geopolymerization.
3. **Aggregates**:
   a. **Coarse Aggregates:** crushed stone passing through a 20 mm sieve, conforming to IS: 383.
   b. **Fine Aggregates:** river sand passing through a 4.75 mm sieve with good grading and cleanliness.

4. **Fibers**:
    a. **Steel Fibers:** hooked-end type with an aspect ratio of approximately 60, added at dosages of 0%, 0.5%, 1.0%, and 1.5% by volume of concrete.
5. **Admixture**:
    a. **Superplasticizer**: polycarboxylate based high-range water reducer was used to enhance workability, particularly in fiber-rich mixes.

3.2 Mix Proportions

The mix Design for the G50 Grade of GPC adopted from the literature "Muhammad N.S.Hadi, Shehroze Ali, and M.Neaz Sheikh (2021)". The Mix proportions are shown in Table 3.1. Trials were conducted and the following proportions (Table 3.4) and used in the present study.

Table 3.1 Mix proportions for G50 grade of concrete

Material	Quantity (kg/m^3)
Fly ash	270
GGBS	180
Coarse Aggregate	1295
Fine Aggregate	552
Sodium Silicate	112.5
Sodium Hydroxide	45
Super Plasticizer	34.7
Water	86.4

The mix was proportioned to achieve M50 grade strength. The alkaline liquid-to-binder (AL/B) ratio was maintained at 0.4, and the sodium silicate to sodium hydroxide ratio was kept at 2.5. The aggregate-to-binder ratio was approximately 3:1.

The addition of steel fibers to geopolymer concrete significantly influences its mechanical properties. Fiber contents ranging from 0.5% to 1.5% by volume enhance compressive, tensile, and flexural strength, as well as fracture toughness. Lower dosages offer modest strength gains with minimal impact on workability, while higher contents improve ductility and crack resistance but may reduce workability due to fiber clustering. The optimal fiber content depends on the specific structural application and the desired balance between strength and workability. Overall, appropriate fiber incorporation enhances the durability and structural performance of geopolymer concrete in demanding environments.

A summary of the fiber volume fractions used for Test Matrix is shown Table 3.2:

Table 3.2 Test Matrix - Fiber Volume Fractions

Fiber Volume Fraction (%)	Compressive strength test	Split tensile test	Flexural strength test	Bending Strut and Tie
0%	3	3	3	3
0.5%	3	3	3	3
1%	3	3	3	3
1.5%	3	3	3	3

3.3 Specimen Preparation

In this study, total 48 specimens are casted and four different fibre volume fractions 0%,0.5%,1% and 1.5% were used. For each proportion a total 12 specimens were casted for four different types of tests. Concrete was mixed manually using a rotating drum mixer. Dry ingredients (fly ash, GGBS, and aggregates) were first mixed, followed by the addition of alkaline activator solution and superplasticizer. Steel fibers were gradually added to ensure even dispersion.

The concrete was cast into the following specimen molds:

Fig 3.1 Casting of Cubes, Cylinders and Prisms

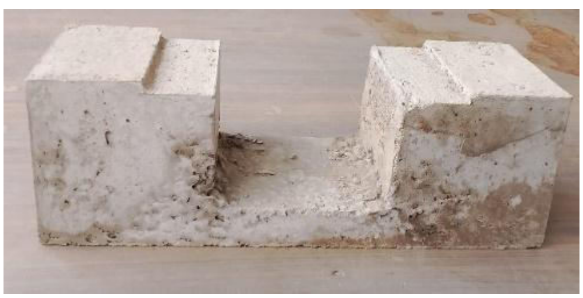


Fig 3.2 casting of Strut and Tie

Fig 3.3 Steel Fiber dispersion in GPC

Table 3.3 Dimensions and number of specimens

Test Type	Types of specimens	Dimension of the specimen (mm)	Number of specimens
Compressive strength Test	Cube	150x150x150	12
Split Tensile Test	Cylinder	150x300	12
Flexural strength test	Prism	100x100x500	12
Bending strut and tie	Strut and tie model	100x150x500	12

All specimens were cured under ambient conditions (room temperature) for 28 days.

3.4 Test Methods

After curing, the following tests were conducted in accordance with IS and ASTM standards:

1. **Compressive Strength Test**:

   Conducted on cubes using a compression testing machine as per IS 516.

2. **Split Tensile Strength Test**:

   Performed on cylinders according to IS 5816:1999. Specimens were loaded diametrically to induce tensile failure.

3. **Flexural Strength Test**:

   Performed on beam specimens using a two-point loading setup in accordance with IS 516, determining the modulus of rupture.

4. **Bending Strut and Tie Test**:

   Used to simulate tensile force transfer mechanisms. Strains, deflections, and failure modes were recorded to understand crack patterns and ductility under indirect tension.

4. Results and Discussion

The mechanical test results of M50 grade geopolymer concrete (GPC) incorporating steel fibers at different volume fractions (0%, 0.5%, 1.0%, and 1.5%) are evaluated. The evaluation includes compressive strength, split tensile strength, flexural strength, and strut-and-tie behaviour. The results are analyzed to determine the influence of steel fibers on strength enhancement and failure characteristics and are as follows:

4.1 Compressive Strength

The cube compressive strength results are presented in table 4.1 and fig 4.1. The results show that the 0.5% fibre volume fraction Specimens compressive strength is increased by 2.69% when compared with the 0% fibre volume fraction specimens. In case of 1% fibre volume fraction mix compressive strength is increased by 10.96% compared with 0% fibre volume fraction specimens. In the case of 1.5% fibre volume fraction specimen’s compressive strength is increased by 0.09% when compared with 0% fibre volume fraction specimens. Here, it is relatively low and here the optimum fibre volume fraction is 1%. The failed specimen is shown in fig 4.2.

Table 4.1 Compressive Strength Results (MPa):

Fiber volume fraction	Specimen			Average
	1	2	3	
0%	50.12	51.23	50.2	50.15
0.50%	51.04	51.45	52.01	51.5
1%	58.75	49.5	58.72	55.65
1.50%	50.25	49.72	50.63	50.2

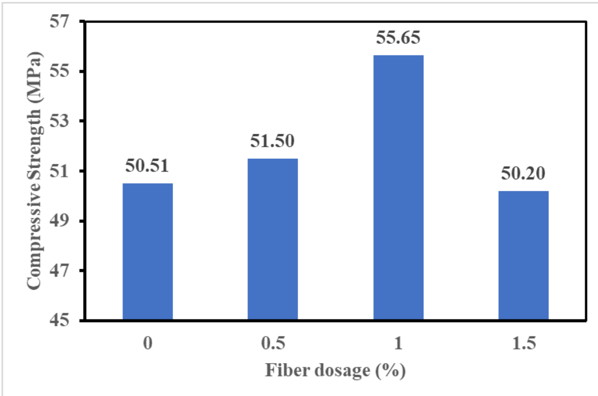
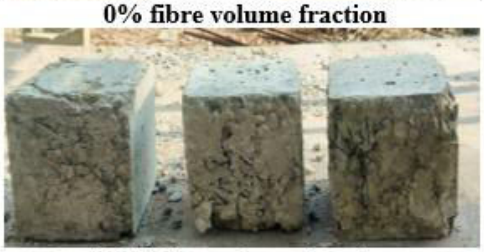


Fig 4.1: Compressive strength results

0% fibre volume fraction



0.5% fibre volume fraction

1% fibre volume fraction

1.5% fibre volume fraction

Fig 4.4: Failure of Compressive test specimens

4.2 Split Tensile Strength

The Split tensile strength results are presented in table 4.2 and fig 4.3. A significant increase in split tensile strength was recorded with increasing fiber content. Steel fibers helped in bridging the internal cracks formed due to tensile stress. At 1.0% fiber content, the split tensile strength increased by approximately 40% compared to the control mix.

Table 4.2 Split tensile strength (MPa) results:

Fiber volume fraction	Specimen			Average
	1	2	3	
0%	2.8	3.26	3.14	3.066
0.50%	3.5	3.3	3.36	3.386
1%	3.72	3.81	3.78	3.77
1.50%	2.15	3.12	2.76	2.6

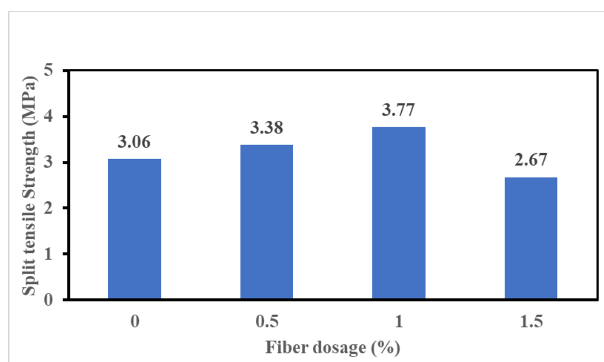
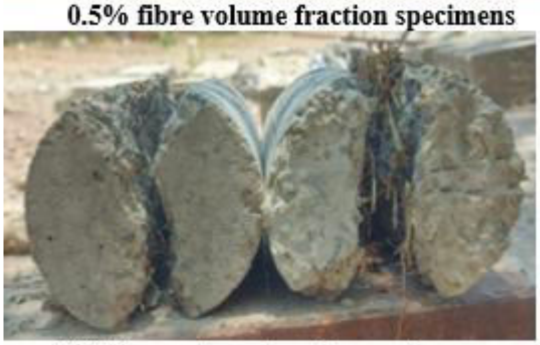


Fig 4.3: Split Tensile test results

0% fibre volume fraction specimens

0.5% fibre volume fraction specimens



1% fibre volume fraction specimens

1.5% fibre volume fraction specimens

Fig 4.4: Failure of Split tensile test specimens

4.3 Flexural Strength

The Flexural strength results are presented in table 4.3 and fig 4.5. Flexural strength also showed notable improvement with the incorporation of steel fibers. Fibers effectively resisted crack growth under bending stresses and enhanced the post-cracking load-bearing capacity. The flexural strength increased by more than 50% at 1.0% fiber content.

Table 4.3 Flexural Strength (MPa) test results:

Fiber volume fraction	**Specimen**			**Average**
	1	**2**	**3**	
0%	4.4	4.17	3.75	4.106
0.50%	4.13	4.23	4.32	4.226
1%	4.57	4.6	4.03	4.4
1.50%	4.4	4.25	4.16	4.27

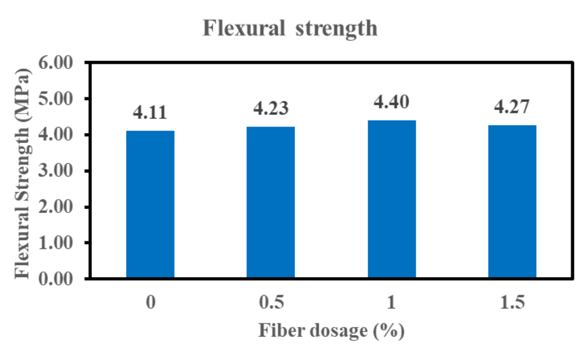


Fig 4.5: Flexural Strength test Results

0% fibre volume fraction specimens

0.5% fibre volume fraction specimens

1% fibre volume fraction specimens

1.5% fibre volume fraction specimens

Fig 4.6: Failure of Flexure test specimens

4.4 Strut-and-Tie Behaviour

Strut-and-tie tests revealed an increase in load capacity, energy absorption, and crack arresting characteristics with steel fiber addition. Control specimens failed in a brittle manner, whereas fiber-reinforced specimens displayed distributed cracking and gradual failure. Peak performance was observed at 1.0% fiber content, indicating a balance between fiber efficiency and matrix integrity.

Table 4.4 Strut and Tie Results:

Fiber volume fraction	Specimen			Average
	1	2	3	
0	0.467	0.607	0.637	0.57
0.5	2.71	2.59	1.428	2.242
1	4.363	3.562	4.055	3.993
1.5	3.041	4.424	4.022	3.829

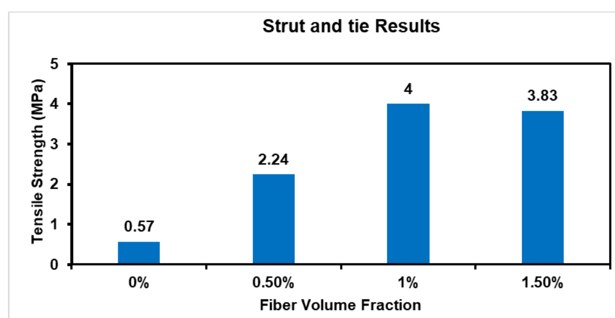


Fig 4.7: Strut and Tie Results

0% fibre volume fraction specimens

0.5% fibre volume fraction specimens

1% fibre volume fraction specimens

1.5% fibre volume fraction specimens

Fig 4.8: Failed strut and tie specimens

4.5 Failure Modes

- Without Fibers: Brittle failure with a single dominant crack.
- With Fibers: Multiple fine cracks, delayed crack widening, improved ductility.
- At 1.5%, clumping was observed in a few specimens, which slightly reduced uniform crack propagation**.**

4.6 Relationship between different tests

Asper IS 456: 2000 the tensile strength of concrete is given by $0.7\sqrt{f_{ck}}$. The results of tests conducted in the present study are presented and compared with IS code formula are shown in fig 4.9. The IS prescribed formula gives over estimated value than all other tests conducted in the study. The flexural strength results are relatively close to the IS code formula and split tensile strength values are lower than the code formula. The strut and tie formula is not representing the actual tensile strength values for concrete without fibers and reasonably providing for the concrete with fibers.

The comparative analysis reveals that the 1% steel fiber dosage offers the optimum balance between improved tensile performance across all test methods. While none of the experimental methods exceed the IS code value of $0.7\sqrt{f_{ck}}$, the strut-and-tie and flexure tests show strengths close to this empirical formula value, particularly at the optimal dosage. The differences between experimental and code-based values emphasize the need to consider realistic material behavior and fiber dispersion efficiency in practical design.

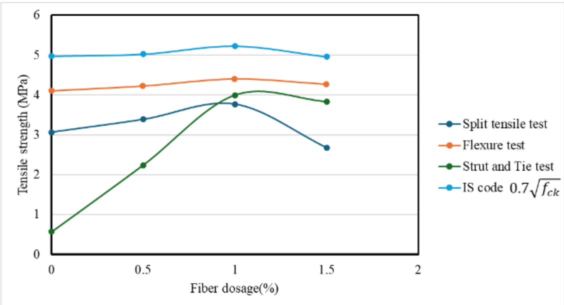


Fig 4.9: Comparison of test results

4.7 Discussion

The experimental results confirm that incorporating steel fibers significantly improves the tensile and flexural strength of M50 grade geopolymer concrete. As observed in previous studies by Thomas and Ramaswamy (2007), the compressive strength increases marginally with fiber addition, while tensile-related properties see more substantial gains due to enhanced crack-bridging and energy absorption [1].

In this study, the split tensile and flexural strength improved by over 40% and 50%, respectively, at 1.0% fiber dosage. These results are consistent with Song and Hwang (2004), who reported notable tensile strength improvements with increasing fiber volume, although they cautioned that higher contents can impair workability [2]. Similarly, a slight reduction in performance at 1.5% fiber content in the current work may be attributed to fiber clumping and reduced mix homogeneity, as highlighted by Marcalikova et al. (2020) [3].

The improved crack resistance and distributed failure modes observed align with known mechanisms of fiber reinforcement, further validating the use of steel fibers in enhancing GPC's tensile behaviour. Overall, the findings support existing literature while extending it to high-strength GPC, highlighting 1.0% fiber volume as an optimal content.

5. Conclusions

- The inclusion of synthetic fibers significantly enhances the mechanical properties of concrete. 1% fiber volume fraction resulted in an increase of 10.96% in compressive strength, 22.96% in split tensile strength, and 7.16% in flexural strength compared to plain concrete.
- Among the tested fiber volume fractions, 1% was consistently found to be the optimum level for enhancing strength across all mechanical and structural parameters, making it a practical and efficient choice for fiber-reinforced concrete design.
- The 1% steel fiber dosage provides the most effective improvement in tensile performance, with flexure and strut-and-tie test results approaching the IS code empirical value and strut and tie method may be used only for the mixes with fibers.

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