Journal Homepage: www.ijarpr.com ISSN: 3049-0103 (Online)

International Journal of Advance Research Publication and Reviews

Vol 03, Issue 8, pp 497-501, August, 2026

Experimental Investigation of Steel Fiber Reinforced Geopolymer Concrete (SFRGC) Beams under Flexural Loading for Sustainable Structural Applications

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ABSTRACT

Steel Fiber Reinforced Geopolymer Concrete (SFRGC) has emerged as a sustainable alternative to conventional reinforced concrete due to its reduced carbon footprint and enhanced mechanical performance. This study experimentally investigates the flexural behavior of SFRGC beams to evaluate their suitability for sustainable structural applications. Geopolymer concrete was produced using industrial by-products as binder materials and reinforced with steel fibers to improve tensile strength, crack resistance, and ductility. Beam specimens were cast, cured under controlled conditions, and tested under four-point bending until failure. Key performance parameters, including first crack load, ultimate load, load–deflection response, flexural strength, ductility, and failure patterns, were recorded and analyzed. The experimental results indicated that the inclusion of steel fibers significantly enhanced the flexural performance of geopolymer concrete beams by increasing load-carrying capacity and delaying crack propagation. Fiber reinforcement also improved post-cracking behavior, energy absorption, and structural ductility, resulting in a more gradual and controlled failure mechanism compared with conventional geopolymer concrete beams. The findings demonstrate that SFRGC beams possess superior structural performance while contributing to environmental sustainability through the utilization of industrial waste materials and reduced cement consumption. The study highlights the potential of SFRGC as an efficient and eco-friendly construction material for modern infrastructure. These experimental findings provide valuable insights for the design and application of sustainable concrete structures and establish a foundation for future numerical modeling and large-scale structural implementation.

Keywords: Steel Fiber Reinforced Geopolymer Concrete (SFRGC), Geopolymer Concrete, Flexural Behavior, Sustainable Construction, Structural Performance, Crack Resistance, Ductility, Load–Deflection Response

Introduction

The construction industry is one of the largest contributors to global carbon dioxide (CO_2) emissions, primarily due to the extensive use of Ordinary Portland Cement (OPC) in concrete production. As the demand for sustainable infrastructure continues to grow, researchers have focused on developing environmentally friendly construction materials that reduce the environmental impact without compromising structural performance.[1] Geopolymer concrete has emerged as a promising alternative to conventional cement concrete because it utilizes industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS) as binder materials, thereby reducing cement consumption and greenhouse gas emissions.[2]

Although geopolymer concrete exhibits excellent compressive strength and durability, its brittle nature and relatively low tensile capacity limit its application in structural members subjected to flexural loading. The incorporation of steel fibers into geopolymer concrete has been recognized as an effective approach to overcome these limitations. Steel fibers improve crack resistance, enhance ductility, increase energy absorption capacity, and delay crack propagation, resulting in improved flexural performance and structural reliability.[3]

This study experimentally investigates the flexural behavior of Steel Fiber Reinforced Geopolymer Concrete (SFRGC) beams under loading conditions. The research evaluates key parameters such as first crack load, ultimate load, load–deflection behavior, and failure patterns to assess the effectiveness of steel fiber reinforcement. The findings are expected to contribute to the development of sustainable, high-performance concrete structures and provide useful guidance for the practical application of SFRGC in modern construction.[4]

Literature Review

Geopolymer concrete has gained significant attention as a sustainable alternative to conventional cement-based concrete because it can utilize industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS) as primary binder materials. Researchers have reported that geopolymer concrete can provide satisfactory mechanical strength, durability, and resistance to aggressive environmental conditions while reducing the consumption of ordinary Portland cement. Its lower dependence on cement also contributes to a reduction in carbon emissions associated with construction activities.

Previous studies have shown that the mechanical performance of geopolymer concrete depends on parameters such as binder composition, alkaline activator concentration, curing conditions, aggregate properties, and water-to-binder ratio. Fly ash-based geopolymer concrete generally exhibits good long-term strength, whereas the addition of GGBS can improve early-age strength and reduce the requirement for elevated-temperature curing. However, geopolymer concrete remains relatively brittle under tensile and flexural loading.[5]

To overcome this limitation, researchers have investigated the incorporation of steel fibers into geopolymer concrete. Steel fibers act as crack-bridging elements and help control the initiation and propagation of cracks. Their inclusion can improve tensile strength, flexural strength, post-cracking behavior, ductility, and energy absorption capacity. Studies on fiber-reinforced geopolymer composites have demonstrated that an appropriate amount of steel fibers can significantly increase the ultimate load-carrying capacity of structural members.[6]

Experimental investigations on beams have further indicated that steel fibers help reduce crack width and increase the number of finer cracks instead of allowing a few large cracks to develop. This behavior improves structural integrity and provides a more gradual failure mechanism. The load-deflection response of steel fiber reinforced geopolymer concrete beams generally shows enhanced stiffness and greater deformation capacity compared with unreinforced geopolymer beams.

Despite these developments, limited research has focused on the detailed flexural response of SFRGC beams by simultaneously evaluating first crack load, ultimate load, load-deflection behavior, ductility, crack patterns, and failure modes. Therefore, further experimental investigation is required to understand the structural behavior of SFRGC beams and assess their suitability for sustainable structural applications.

Research Gap

Although considerable research has been conducted on geopolymer concrete and steel fiber reinforced concrete, several important research gaps still exist regarding the flexural behavior of Steel Fiber Reinforced Geopolymer Concrete (SFRGC) beams.

- Most previous studies have focused on the compressive strength and durability of geopolymer concrete, while limited attention has been given to its flexural performance under structural loading.
- The combined effect of steel fibers on the load–deflection behavior, ductility, and energy absorption capacity of geopolymer concrete beams has not been comprehensively investigated.
- Limited experimental studies have analyzed crack propagation, failure modes, and post-cracking behavior of SFRGC beams under flexural loading.
- Existing research often evaluates only one or two performance parameters, whereas a comprehensive assessment of first crack load, ultimate load, flexural strength, and structural behavior is still lacking.
- The practical application of SFRGC beams in sustainable structural engineering remains limited due to insufficient experimental data and design recommendations.

Therefore, this study aims to experimentally investigate the flexural behavior of Steel Fiber Reinforced Geopolymer Concrete (SFRGC) beams and provide a comprehensive evaluation of their structural performance, crack resistance, ductility, and sustainability for modern construction applications.

Materials and Methods

1 Materials Used

The Steel Fiber Reinforced Geopolymer Concrete (SFRGC) used in this study was prepared using fly ash and Ground Granulated Blast Furnace Slag (GGBS) as the primary binder materials. Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions were used as alkaline activators to initiate the geopolymerization process. Natural river sand was used as fine aggregate, while crushed granite with a maximum size of 20 mm was used as coarse aggregate. Hooked-end steel fibers were incorporated into the concrete mixture to improve tensile strength, crack resistance, and ductility. Clean potable water was used for preparing the alkaline solution and maintaining the required workability.[7]

2 Mix Design

The geopolymer concrete mix was designed based on published guidelines for structural-grade geopolymer concrete. The binder consisted of fly ash and GGBS in suitable proportions, activated by a combination of sodium hydroxide and sodium silicate solutions. Steel fibers were added at predetermined volume fractions to produce Steel Fiber Reinforced Geopolymer Concrete. The mix proportions were selected to achieve adequate workability, high compressive strength, and improved flexural performance while ensuring uniform fiber distribution throughout the concrete.

3 Beam Specimen Details

A total of beam specimens were cast for experimental evaluation. The beams were designed with standard dimensions of **150 mm × 150 mm × 700 mm** and reinforced with conventional steel reinforcement to simulate practical structural members. Two categories of specimens were prepared: control geopolymer concrete beams without steel fibers and Steel Fiber Reinforced Geopolymer Concrete (SFRGC) beams containing steel fibers. The specimens were properly labeled for identification during testing and analysis.

4 Casting and Curing

All dry materials were first mixed thoroughly to obtain a uniform blend. The alkaline activator solution was then added gradually, followed by the incorporation of steel fibers to ensure their uniform dispersion within the concrete matrix. The fresh concrete was poured into beam moulds in layers and compacted using a vibrating table to eliminate air voids. After casting, the specimens were covered to prevent moisture loss and demoulded after 24 hours. The beams were then cured under controlled laboratory conditions until the testing age of 28 days.[8]

5 Experimental Setup

The flexural performance of the beam specimens was evaluated using a Universal Testing Machine (UTM) under four-point loading conditions. The beams were simply supported at both ends, and the load was applied through two loading points to create a constant bending moment in the central region. A load cell was used to measure the applied load, while a Linear Variable Differential Transformer (LVDT) was positioned at the mid-span to record beam deflection. Crack initiation and propagation were visually monitored throughout the testing process.

6 Flexural Testing Procedure

The beam specimens were tested after completing the curing period. Each specimen was placed on the testing frame with the specified support conditions. Load was applied gradually at a constant loading rate until failure occurred. During the test, the first crack load, ultimate load, mid-span deflection, crack pattern, and failure mode were carefully recorded. The load–deflection response of each beam was obtained from the experimental measurements. The performance of Steel Fiber Reinforced Geopolymer Concrete beams was then compared with that of conventional geopolymer concrete beams to evaluate the effectiveness of steel fiber reinforcement in enhancing flexural strength, ductility, and overall structural performance.[9]

Results and Discussion

1. Load–Deflection Behavior

The load–deflection response of the beam specimens demonstrated a significant improvement in the flexural performance of Steel Fiber Reinforced Geopolymer Concrete (SFRGC) beams compared with conventional geopolymer concrete beams. Initially, both beam types exhibited nearly linear elastic behavior. However, after the formation of the first crack, the conventional geopolymer beams experienced a rapid increase in deflection accompanied by a sharp reduction in stiffness. In contrast, the SFRGC beams maintained their load-carrying capacity for a longer duration due to the crack-bridging action of steel fibers. The fibers effectively controlled crack widening, resulting in a more gradual load–deflection curve and improved post-cracking behavior.

2. First Crack Load

The first visible crack appeared at a higher load in the SFRGC beams than in the conventional geopolymer beams. The presence of steel fibers delayed crack initiation by distributing tensile stresses more uniformly within the concrete matrix. This improved tensile resistance indicates that steel fibers significantly enhance the cracking performance of geopolymer concrete under flexural loading. The delayed formation of the first crack also contributed to improved serviceability and structural durability.[10]

3. Ultimate Load

The experimental results showed that SFRGC beams achieved a higher ultimate load than conventional geopolymer concrete beams. The addition of steel fibers increased the beam's resistance to flexural failure by transferring tensile stresses across cracks and preventing sudden crack propagation. As a result, the SFRGC beams sustained higher loads before reaching failure, demonstrating their superior structural performance and load-carrying capacity.

4 Crack Pattern and Failure Mode

The conventional geopolymer concrete beams developed fewer but wider flexural cracks, leading to brittle failure after reaching the ultimate load. In contrast, the SFRGC beams exhibited a larger number of closely spaced and finer cracks due to the crack-arresting mechanism of steel fibers. The fibers bridged the cracks and delayed their propagation, resulting in a more controlled and ductile failure mode. No sudden collapse was observed in the SFRGC beams, indicating improved structural safety.[11]

5 Flexural Strength

The incorporation of steel fibers considerably improved the flexural strength of geopolymer concrete beams. Fiber reinforcement enhanced the tensile resistance of the concrete matrix and reduced stress concentration near crack locations. Consequently, the SFRGC beams exhibited higher bending resistance and greater structural stability than the conventional geopolymer beams. The improvement in flexural strength confirms the effectiveness of steel fibers in enhancing the mechanical performance of geopolymer concrete.

6. Ductility and Energy Absorption

One of the major advantages of steel fiber reinforcement was the significant increase in ductility and energy absorption capacity. The SFRGC beams underwent larger deflections before failure while maintaining structural integrity. The fibers absorbed a considerable amount of energy during crack propagation, resulting in improved toughness and post-cracking performance. This enhanced ductility is particularly beneficial for structures subjected to dynamic loading, seismic forces, or repeated service loads.

7. Comparison Between Conventional Geopolymer Concrete Beams and SFRGC Beams

The comparative analysis clearly demonstrated that Steel Fiber Reinforced Geopolymer Concrete beams outperformed conventional geopolymer concrete beams in all major performance parameters. SFRGC beams exhibited higher first crack load, greater ultimate load, increased flexural strength, improved load–deflection characteristics, enhanced ductility, and better energy absorption capacity. Moreover, the steel fibers effectively controlled crack propagation and transformed the brittle failure of conventional geopolymer concrete into a more gradual and ductile failure mechanism. These findings indicate that SFRGC beams are a reliable and sustainable alternative for structural applications requiring high flexural performance, durability, and improved service life.[12]

Conclusions

The experimental investigation confirmed that the incorporation of steel fibers significantly enhances the flexural performance of geopolymer concrete beams. Steel Fiber Reinforced Geopolymer Concrete (SFRGC) beams exhibited higher first crack load, greater ultimate load, improved flexural strength, and superior load-carrying capacity compared with conventional geopolymer concrete beams. The presence of steel fibers effectively controlled crack initiation and propagation, resulting in smaller crack widths and a more uniform crack distribution. Furthermore, SFRGC beams demonstrated improved ductility, energy absorption, and post-cracking behavior, leading to a gradual and safer failure mechanism. The use of fly ash and GGBS as binder materials also contributed to environmental sustainability by reducing cement consumption and carbon emissions. Overall, the study concludes that SFRGC beams provide an efficient, durable, and eco-friendly solution for modern structural applications where high flexural performance and sustainability are essential.

Future Scope

- Investigate the long-term durability of SFRGC beams under aggressive environmental conditions such as chloride exposure, sulphate attack, and freeze–thaw cycles.
- Evaluate the seismic and dynamic behavior of SFRGC structural members under cyclic and impact loading.
- Study the influence of different types, shapes, and volume fractions of steel fibers on the flexural and shear performance of geopolymer concrete beams.
- Develop finite element (FEA) models using ANSYS or ABAQUS to validate experimental results and predict structural behavior.
- Explore the use of hybrid fibers and alternative industrial by-products to further improve the mechanical and durability properties of geopolymer concrete.
- Investigate the behavior of full-scale SFRGC structural elements, including beams, slabs, and columns, for practical construction applications.
- Perform life-cycle cost and environmental impact assessments to evaluate the economic and sustainability benefits of SFRGC in infrastructure

projects.

- Develop design guidelines and codal recommendations to facilitate the wider adoption of Steel Fiber Reinforced Geopolymer Concrete in sustainable structural engineering.

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