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INNOVATIVE SOLUTIONS FOR SUSTAINABLE BUILDING STRENGTHENING: GLASS FIBER REINFORCED CONCRETE

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Abstract- Steel-reinforced Glass Fiber Reinforced Concrete (SGFRC) is a promising alternative to conventional construction materials, offering enhanced structural performance and sustainability. This paper presents a review of recent research on SGFRC in construction. By integrating fine glass fibers (GF) into steel-reinforced concrete matrix, SGFRC demonstrates remarkable tensile strength, flexural performance, and durability, enabling resilient and long-lasting structures. The eco-friendly nature of glass fibers further contributes to construction sustainability by reducing carbon footprints. This study explores manufacturing techniques and formulation strategies to optimize SGFRC properties for strengthening, energy-efficient, and environmentally conscious buildings. Experimental examinations, including flexural strength (FS), pre-crack/post-crack/total energy absorption, and toughness index, compare SGFRC with steel-rebar-reinforced plain concrete (SPC). Both adopt a mix design ratio of 1:2:4 (Cement: Sand: Aggregates) with a water-cement ratio of 0.7. GFRC incorporates 5% of 5cm lengthy GF by mass of cement, leading to reduced density and slump. Findings highlight SGFRC's superiority in FS and other flexural strength properties, emphasizing GFRC's significance for enhancing structural performance and promoting sustainable construction practices.

Keywords- Construction Sustainability, Enhanced Structural Performance, Steel-reinforced Glass Fiber Reinforced Concrete (SGFRC), Strengthening Building Structures.

1 Introduction

In the field of construction materials, the quest for sustainable alternatives to conventional materials has become increasingly vital to address the challenges posed by environmental concerns and resource scarcity [1]. One promising solution that has garnered significant attention is Steel-reinforced Glass Fiber Reinforced Concrete (SGFRC) [2]. This innovative composite material offers a compelling combination of enhanced structural performance and sustainability, making it a potential game-changer in the construction industry [3]. The following paper presents a review of recent research on SGFRC in construction, shedding light on its unique properties and contributions to sustainable building practices.

SGFRC's exceptional attributes can be attributed to the incorporation of fine glass fibers (GF) into the steel-reinforced concrete matrix. This integration bestows the concrete with remarkable flexural strength, improved tensile performance, and exceptional durability, enabling the construction of resilient and long-lasting structures that can withstand the test of time and environmental challenges [4][5][6]. Moreover, the eco-friendly nature of GF plays a significant role in enhancing the overall sustainability of the construction industry. By reducing carbon footprints, SGFRC demonstrates its commitment to environmentally conscious construction practices [7].

As the significance of sustainability grows in the construction sector, understanding and optimizing the properties of SGFRC become paramount. The research presented in this study offers novelty and significant contributions to the field of construction materials and sustainable building practices. This study takes a deep dive into various manufacturing techniques and formulation strategies employed to maximize the performance of SGFRC [8][9]. Architects and engineers will gain valuable insights from these findings, enabling them to design energy-efficient and environmentally conscious buildings that align with sustainable construction principles [10]. The study's key focus on enhancing the pre and post-cracking behaviors of SGFRC in pursuit of a sustainable approach to strengthening building structures is a notable aspect of the research. Moreover, the exceptional impact resistance and good ductility of glass fibers distinguish them among artificial fibers [11], adding to the novelty of the study. By evaluating the long-term serviceability of strengthened, long-lasting structures, this research addresses a critical aspect of sustainability in construction. The experimental exploration of flexural strength, energy absorption, and toughness index contributes valuable knowledge to the potential of GFRC reinforced with steel rebar for achieving both structural strengthening and sustainable construction goals. Through an advanced understanding of SGFRC's mechanical properties, this study endeavors to make a significant contribution to the realization of more resilient and eco-conscious building solutions.

2 Experimental Procedures

2.1 Primary Materials

Steel-rebar-reinforced plain concrete (SPC) and steel-reinforced glass fiber reinforced concrete (SGFRC) are composed of several key ingredients. These include Ordinary Portland cement, locally sourced sand, aggregates, potable water, and a specific mass percentage of glass fibers relative to the amount of cement used in the mixture.

2.2 Glass Fibers Preparation

Obtaining glass fibers of the required length can be a laborious and time-consuming process, as they are commonly available in the form of glass sheets. In order to achieve the desired length, glass fibers are carefully pulled out from the sheet and then precisely chopped to the required length of 5 cm. Figure 1 provides a visual representation of this process, showcasing the glass fibers after they have been pulled from the sheet and cut to the specified length.

Figure 1: Prepared Glass Fibers

2.3 Development of Concrete Mixtures and Casting Techniques

The mix-design, water-cement ratio, and fiber addition for steel-rebar-reinforced plain concrete (SPC) and steel-reinforced glass fiber reinforced concrete (SGFRC) are provided in Table 1. To compensate for the added fiber mass, an equal measure (mass) of aggregate is deducted from the total mass of aggregates. All materials are added based on the mass of cement. The concrete mix is prepared using a drum-type concrete mixer. All ingredients, including water, are placed in the mixer, and it is rotated for a duration of five minutes to ensure thorough mixing.

In the preparation of GFRC, the ingredients of the concrete, along with the fibers, are added to the mixer layer by layer to prevent the formation of lumps. Approximately two-thirds of the required water is added, based on the water-cement ratio of 0.7, which is the same as that used for PC. The concrete mixer undergoes rotation for three minutes initially. Afterward, the remaining one-third of the water is introduced to the GFRC mixture, and the drum-type concrete mixer continues to rotate for an additional two minutes. The workability of the GFRC is observed, and it is ensured that the added water is sufficient to achieve the desired workability. Before pouring the GFRC into molds, a slump cone test is performed to assess the consistency of the mixture.

The GFRC mixture is introduced into molds in a series of three layers, and each layer undergoes compaction with 25 blows from a steel rod. To promote self-compaction and remove air voids, the molds are lifted to a height of approximately 200-300 mm and then dropped onto the floor. After a pouring duration of 24 hours, the specimens are demolded. All specimens are subsequently immersed in water at room temperature for a curing period of 28 days before testing.

Table 1 Mix-design, Water-cement ratio and Glass Fibers Content of SPC and SGFRC

Mixes	Mix-design ratio (Cement:Sand:Aggregate)	Water-cement ratio	Glass Fibers by Mass of Cement (%)	Fibers Cut Length (cm)
SPC	1:2:4	0.7	--	--
SGFRC	1:2:4	0.7	5	5

2.4 Casting of Beam-lets and Reinforcement Details

For both Steel-Rebar-Reinforced Plain Concrete (SPC) and Steel-Reinforced Glass Fiber Reinforced Concrete (SGFRC), beam-lets with dimensions of 102 mm width, 102 mm depth, and 457 mm length were cast. To compare the flexural properties of the two materials, a total of four beam-lets are cast, with two beam-lets for SPC and two beam-lets for SGFRC with steel rebars.

For each composite, the average of the results obtained from the two specimens is considered as the final value. The reinforcement details for both SPC and SGFRC, including steel rebars, are provided in Figure 2.

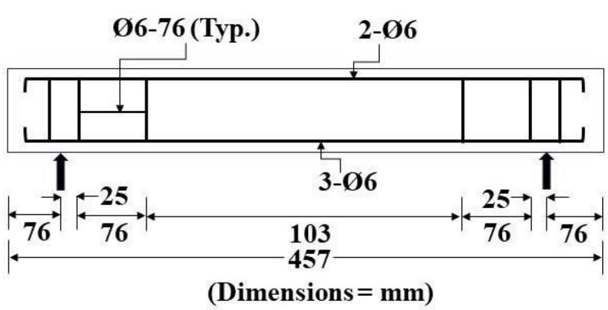

Figure 2: Details of beam under consideration

3 Research Methodology

To assess the workability and flow characteristics of fresh concrete in both plain concrete (PC) and glass fiber reinforced concrete (GFRC) mixes, the slump cone test is conducted following ASTM C143/C143M-15a [12] guidelines. This standardized test allows for a fair comparison of workable behavior under identical mix designs and water-cement ratios. The test helps to attribute any differences in workability to the presence of glass fibers in the GFRC mixture, aiding in evaluation during casting and placement processes.

The densities of steel-rebar-reinforced plain concrete (SPC) and steel-reinforced glass fiber reinforced concrete (SGFRC) beam-lets are computed using ASTM C138/C138M-16 [13]. An electric weighing balance is used to measure the masses, and volumes are calculated manually based on dimensions. These ASTM standards ensure accurate density values for both SPC and SGFRC, facilitating quantitative material property comparison.

To determine the flexural strength of SPC and SGFRC beam-lets, ASTM C78/C78M-15b [14] is conducted. A servo-hydraulic testing machine subjects the reinforced beam-lets to a flexural test, measuring deflections with a dial gauge. The loading rate of 100-250 pounds/second are used in all tests. It may be noted that the loading rate was controlled manually. The test data provides parameters like first crack load (P_f), maximum-load (P_m), ultimate-load (P_u), maximum deflection (Δ), crack strength at ultimate-load, and failure modes, offering insights into the strength characteristics and behavior of the composites.

Additionally, various performance indicators are determined, such as the flexural strength (FS), energy-absorption up to first crack (E_f), energy absorption from first crack to maximum-load (E_m), energy-absorption from maximum-load to ultimate-load (E_u), total energy-absorption (TE), and total toughness index (TTI). These parameters offer a comprehensive understanding of the materials' flexural performance and energy-absorption capacities.

4 Results and Analysis

4.1 Density and Slump of Concrete

The slump of plain concrete (PC) and glass fiber reinforced concrete (GFRC) are given in the third column of Table 2. It is observed that the slump of GFRC is less than that of PC by 20 mm for the same water-cement ratio i.e. 0.7. Thus, the slump of GFRC is reduced by 50% compared to that of PC. As predicted, the decrease in the slump of GFRC is observed due to the presence of glass fibers. Similarly, the observed density of the steel rebar reinforced GFRC is reduced by 91 kg/m^3 as compared to that of steel rebar reinforced PC. The percentage reduction in the density of steel rebar reinforced GFRC is 3.83% when compared with steel rebar reinforced PC. This reduction is due to the presence of glass fibers (less dense in nature) to the concrete.

Table 2 Slump and Densities of PC and GFRC

Mixes	Water-cement ratio	Slump (mm)	Density (kg/m^3)
PC	0.7	40	2375
GFRC	0.7	20	2284

4.2 Behavior of Beam-lets During Flexural Strength Test

4.2.1 Load-deflection Behavior of Beam-lets with Rebars

Figure 3 illustrates the recorded mid-span load-deflection curves of SPC and SGFRC, both of which have flexural reinforcement consisting of 3-Ø6 bars and shear reinforcement of Ø6-76 mm. In Figure 4, the cracks observed during testing of the beam-lets of SPC and SGFRC with flexural reinforcement of 3-Ø6 and shear reinforcement of Ø6-76 mm include the first crack, maximum-load crackes, and ultimate-load cracks. It is noted that before appearance of first crack, the load-deflection curve is increased linearly. The area under the load-deflection curve shows energy absorption of the tested beam-lets. The flexural strength test is employed to observe the behavior of SPC and SGFRC beam-lets. This study reveals specific data, such as length of first crack and the number of cracks at both the maximum-load and ultimate-load. The first crack of SPC and SGFRC is observed at 91.1% and 85.1%, respectively, of their respective highest load. The first crack dimensions in SPC are relatively larger when compared to the corresponding SGFRC specimens. Furthermore, an increase in flexural reinforcement is found to reduce the length of the first crack. Specifically, the length of the first crack is approximately 70 mm for SPC and 57 mm for SGFRC specimens. At maximum-load, the amount of cracks and their dimensions are more for SPC beam-lets as compared to that of SGFRC beam-lets. At ultimate-load, the number of cracks and their dimensions are further larger than that of noted at the maximum-load. The study reveals that SGFRC outperformed SPC in reducing the number and size of cracks, showcasing the significant improvement brought about by the incorporation of glass fibers in the concrete. These findings have promising implications for sustainable construction, as the enhanced performance of SGFRC in reinforced concrete flexural members can contribute to improved seismic performance and greater durability [15].

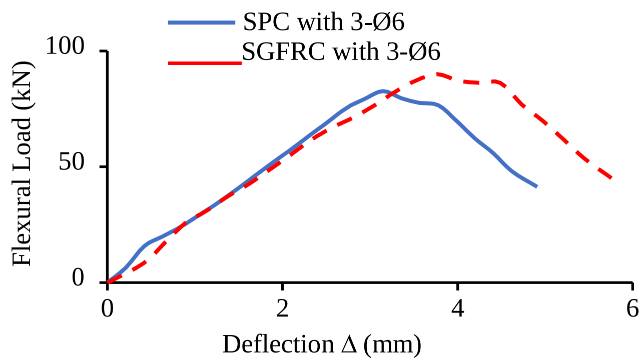

Figure 3: Deflection curve of beam-lets under load

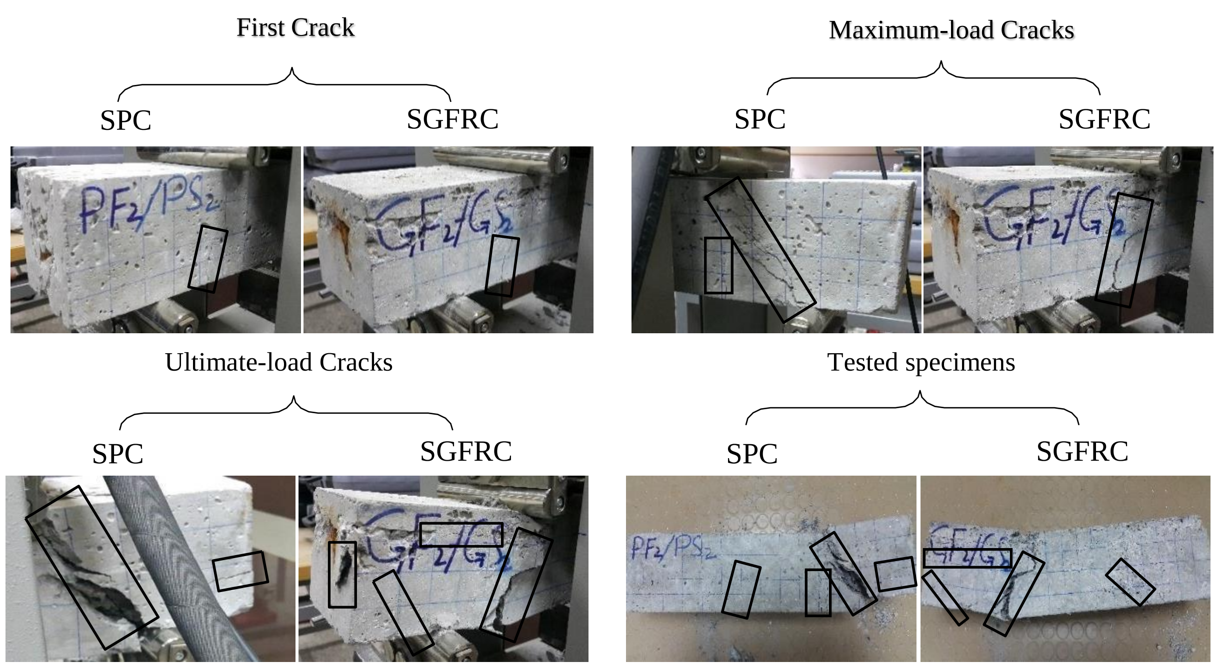

Figure 4: Behavior of beam-lets with flexural rebars reinforcement (3-Ø6) and shear rebars reinforcement (Ø6-76 mm)

4.2.2 Effect of Steel Reinforcement on Strength, Energy Absorption and Toughness Index

Table 3 presents the flexural strength (F.S), energy absorption, and toughness index data of the beam-lets (SPC and SGFRC) with flexural rebar reinforcement of 3-Ø6 and shear rebar reinforcement of Ø6-76 mm. It can be noted that Table 3 presents the averaged values obtained from two beam-lets. The calculated values of F.S for the SPC and SGFRC are 18.0 MPa and 19.6 MPa, respectively. It is increased in SGFRC by 8.9% as compared with that SPC. The calculated values of energy absorption (E_f) up to first crack load of SPC and SGFRC are 104.1 kN.s and 121.7 kN.s, respectively. The E_f of SGFRC is increased by 17.6 kN.s (16.9%) as compared with that SPC. Similarly, the calculated values of energy absorption from first crack to maximum-load (E_m) of SPC and SGFRC are 33.3 kN.s and 60.8 kN.s, respectively. The E_m of SGFRC is increased by 27.5 kN.s (82.6%) in contrast to that of SPC. Likewise, the calculated values of energy absorption from maximum-load to ultimate-load (E_u) of SPC and SGFRC beam-lets are 115.1 kN.s and 145.9 kN.s, respectively. The E_u of SGFRC is increased by 30.8 kN.s (26.8%) in comparison to that of SPC. The T.E is calculated by summing the values of E_f, E_m, and E_u, which is same as the area under the load-deflection curve from zero to the P_u. The T.E of SPC and SGFRC are 252.5 kN.s and 328.3 kN.s, respectively. The T.E of SGFRC is increased by 75.8 kN.s (30%) as compared to that of SPC. The calculated values of total toughness index (T.T.I) of SPC and SGFRC are 2.43 and 2.7, respectively. The T.T.I of SGFRC is increased by 0.27 (11.1%) as compared to that SPC. It may be noted that the F.S, E_f, E_u, TE, TTI are increased due to the presence of glass fiber. The utilization of SGFRC offers a promising approach to enhance the seismic performance of flexural members while promoting sustainable construction practices. The notable improvements in flexural strengths, energy absorptions, and total toughness index achieved through SGFRC demonstrate its potential in increasing the ductility and seismic energy absorption capacity of these structural elements. By incorporating environmentally-friendly GF into the concrete matrix, we not only bolster the earthquake resistance of the flexural members but also contribute to the overall sustainability of the construction industry [16]. These advancements signify a step towards creating resilient and eco-conscious structures that can withstand seismic forces while minimizing their environmental impact.

Table 3 Comparison of strength, energy absorption and toughness index of beams-lets with flexural rebar reinforcement (3-Ø6) and shear rebar reinforcement (Ø6-76 mm)

Specimens	**F.S (MPa)**	**E_f (Up to P_f) (kN.s)**	**E_m (P_f to P_m) (kN.s)**	**E_u (P_m to P_u) (kN.s)**	**T.E (kN.s)**	**T.T.I (-)**
SPC	18.0	104.1	33.3	115.1	252.5	2.43
SGFRC	19.6	121.7	60.8	145.9	328.3	2.70

5 Conclusions and Recommendations

Based on the findings from the experimental work conducted on steel-reinforced glass fiber reinforced concrete (SGFRC) beam-lets, the following conclusions can be drawn regarding the flexural strength and post-cracking behavior in comparison to steel-rebar-reinforced plain concrete (SPC):

1. Workability: GFRC demonstrates a significant 50% reduction in workability compared to plain PC due to the interlocking nature of glass fibers, hindering particle movement during mixing and placing [17][18]. Thus, careful mix design and construction processes are vital for achieving the desired workability and proper compaction of the GFRC mixture.

2. Density: SGFRC shows a 3.83% decrease in density due to the lower-density glass fibers [5] promotes sustainable construction. It lowers material consumption, conserving resources and reducing environmental impacts during concrete production. The lighter composite also enhances transportation and installation energy efficiency, resulting in reduced carbon emissions and environmental impact. SGFRC's sustainability benefits make it an eco-friendly alternative, supporting environmentally conscious and resource-efficient construction practices.

3. Energy Absorption: The notable 30% increase in total energy absorption in SGFRC compared to SPC indicates its enhanced ability to withstand and dissipate energy, making it beneficial for structural performance of strengthened buildings [3]. This higher energy absorption capacity can contribute to safer and more resilient structures, aligning with sustainable construction principles that prioritize long-term durability and safety.

4. Toughness Index: SGFRC exhibits an 11.1% increase in toughness, providing improved crack resistance and longer-lasting structures [19], aligning with sustainable construction practices.

In conclusion, steel-reinforced GFRC offers advantages and challenges for sustainable construction. Despite reduced workability and density, it shows remarkable improvements in energy absorption and toughness, making it promising for resilient structures. Further research on glass fiber content optimization and combined reinforcements is needed to fully leverage GFRC's potential for enhancing seismic performance and eco-friendly structures in alignment with sustainable principles. Acknowledging this pilot study's limitations in the number of tested beams, we aim to establish a foundation for future comprehensive research to draw more robust conclusions.

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