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Enhancing concrete performance through glass fiber reinforcement: A comprehensive mechanical analysis

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Abstract

This research investigates the impact of glass fiber reinforcement on concrete's mechanical properties, emphasizing crack resistance and post-crack behavior. Compressive and tensile tests were conducted on control specimens and those with varying glass fiber content (0%, 0.25%, and 0.5%) over 7, 14, and 28 days. Results reveal that 0.25% glass fiber content optimally enhances both compressive and tensile strength. Compressive stress in 0.25% GFRC excels at 28 days, while tensile stress peaks at 14 days. Notably, 0.5% GFRC exhibits superior post-crack deformation. Higher fiber content positively influences compressive stress, particularly at 28 days. In terms of split tension, 0.25% GFRC excels at 7 and 28 days, while 0.5% GFRC dominates at 14 days. This research underscores the potential of glass fiber reinforcement to significantly improve concrete's mechanical performance, offering valuable insights for resilient construction practices.

Keywords: Glass fiber reinforced concrete, concrete performance, compressive strength, sustainable construction.

1. Introduction

Various technologies have been introduced to improve the tensile and compressive strengths of concrete, including steel fiber reinforced concrete (SFRC), glass fiber reinforced concrete (GFRC), and basalt fiber reinforced concrete. The goal of this research is to incorporate glass fiber into concrete to increase its overall performance. Aggregates, cement, sand, water, and alkali-resistant glass fiber are combined in GFRC, a type of fiber-reinforced concrete. Because of its versatility, it is a popular choice in the construction business, where it may be found in exterior façade panels, pipelines, decorative non-recoverable formwork, and architectural precast concrete. The addition of glass fiber to concrete provides several key benefits, including increased tensile and compressive strength, improved fire resistance, lightweight properties, high mechanical strength, improved crack resistance, higher load carrying capacity, and superior aesthetics, making it an ideal material for architectural projects. The key goals of this research are to improve the tensile, compressive, and energy absorption capacities, mechanical and fracture characteristics, flexural strength, impact and fatigue resistance, deformation capability, toughness, and load-bearing capacity of GFRC. We also intend to strengthen its fire resistance. Related research has looked into the effect of graded glass fibers with variable lengths and volume fractions in GFRC, with increasing fiber length and volume demonstrating improved deformation ability. In further experiments, the mechanical and durability properties of GFRC containing marble and granite dust were investigated. High-strength concrete reinforced with basalt and glass fibers showed good results in terms of compressive strength and ductility. The effect of chopped glass fibers on the mechanical and rheological properties of ceramic concrete has also been investigated, as has the use of glass fiber reinforced polymer (GFRP) in enhancing the seismic behavior of non-ductile columns prone to brittle shear failure. This detailed study adds to the increasing body of knowledge on glass fiber reinforcing. Glass fiber-reinforced polymer composites, utilized since ancient times for containers, have evolved into versatile materials with high strength, flexibility, stiffness, and chemical resistance. Used in modern applications like electronics and aviation, these composites exhibit diverse properties based on manufacturing techniques, making them valuable for various purposes (Sathishkumar, T. P., et al.,). This study of Morampudi et al., 2021 explores the enhanced mechanical properties of glass fiber reinforced polymer composites, emphasizing the impact of different types of glass and manufacturing techniques. The research underscores the positive correlation between increased glass fiber volume and improved properties in terms of strength, flexibility, stiffness, and durability in GFRP composites under mechanical loading. The review of Altin Karataş et al., 2018 comprehensively investigates the machinability properties of carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) composites, analyzing failure mechanisms through various methods such as ANOVA, genetic algorithms, finite elements method (FEM), and microscopy, providing valuable insights for engineering applications.A study investigates the enhancement of concrete properties for marine or hydraulic structures using glass fiber and Portland Pozzolana cement to improve strength, durability, and crack resistance (Dayalan, J., 2017). An experimental study demonstrates that incorporating 0.2% woven roving glass fiber into M25-grade fly ash-based concrete with a w/c ratio of 0.45 effectively improves both compressive strength and durability while maintaining acceptable workability (Dalal, S. P., et al., 2014). Research examines the strength enhancement potential of Luffa fiber-reinforced concrete with partial replacement of cement by Rice Husk Ash (RHA) at varying levels (0–35%) and demonstrates that RHA's amorphous silica content contributes to increased strength and improved resistance against chloride dispersion (Anandaraj, S., et al., 2022). The study of Kizilkanat et al., 2015 compares basalt and glass fiber reinforcement in high-strength concrete, finding that basalt fiber enhances splitting tensile strength, flexural strength, fracture energy, crack resistance, and ductility, outperforming glass fiber at similar dosage levels. The study of Tassew and Lubell, 2014 finds that adding glass fibers (up to 2%) to ceramic concrete with a phosphate cement binder increases flexural strength and direct shear strength, while compressive strength and workability are minimally affected. The study of Rodsin, 2015 demonstrates that the application of glass fiber-reinforced polymer (GFRP) wrapping to non-ductile columns improves shear capacity, enhances concrete confinement, and shifts the failure mode from shear to flexure, thereby enhancing seismic performance. The study of Kasagani and Rao, 2018 investigates the enhancement of concrete performance by using Graded Glass Fibers, combining short and long lengths, leading to improved strength, deformation capacity, energy absorption, workability, and a significant dependence on fiber efficiency characteristics in Glass Fiber Reinforced Concrete. Glass Fiber Reinforced Concrete (GFRC) has evolved since the 1940s, driven by advancements such as zirconium dioxide additives and hybrid mixtures, offering light, strong, fire/weather-resistant, attractive, impermeable materials with potential for low-cost complex construction (Cilt, M., et al., 2018). The study of Mohammed et al., 2021 investigated Ultra-high-performance fiber-reinforced concrete (UHPFRC) with micro-glass fibers (MGF), revealing that lower water-to-binder ratios (w/b) improve mechanical performance and that MGF content of 1.5% to 3% enhances compressive strength up to 160 MPa, with no further improvement beyond 1.5% MGF. The overview of the study of DiBenedetto, 2001 focuses on characterizing interphases in glass fiber and silica reinforced polymers, their effects on mechanical properties, and recent efforts to create strong, monomolecular interphases for improved adhesion and durability in composite materials.

2. Materials and methods of experimentation

2.1 Materials

OPC cement was used to prepare concrete for this experiment, which had a minimum compressive strength of 53 MPa, 53 N/mm2, or 530 kg/cm2 after 28 days. Fine and coarse aggregates were procured from local sources. 20-mm-downgraded stone chips were used as coarse aggregate. Gradation tests, soundness tests, unit weight tests, and specific gravity tests were done according to the AASHTO standard to check whether they are specified according to ACI 211.1-91. For fine aggregate, sieve analysis was done to determine the particle size distribution of the fine aggregate. ACI 211.1-91 does not prescribe specific gradation limits, but a well-graded aggregate (with a range of particle sizes) is generally preferred for good concrete properties. According to ASTM C33, the range for FM is 2.3–3.1 for normal concrete. The specific gravity and clay, silt, and organic content determinations were done for the fine aggregate. Excessive amounts of these materials can lead to reduced workability and durability issues in the concrete. A soundness test was also used. While ACI 211.1-91 doesn't explicitly require a soundness test for fine aggregate, it's still important to ensure the aggregate is sound and will not cause excessive expansion or deterioration when subjected to moisture changes. (Show figure references for consecutive tests.) An additive named Sika Superplasticizer was used to improve the workability and compaction of concrete, increase density, and improve the surface finish of the concrete product. Sika Type F admixture was used to reduce the water demand of the concrete and strengthen it as well, which is specified by ASTM C494. The water source was fresh ground mineral water, approximately pH 7. Table 1 represents the mixed design details of the concrete for this experiment. The properties of the fiber that has been added with the concrete are detailed in Table 2.

Table 1
Mix design details for unit cubic meter concrete of Class-30

Characteristic strength	30 MPa
Target Strength	$(30 + 30 \times (2 \div 3)) = 42\ MPa$
Coarse Aggregate Size	19 mm to 4.75 mm
Fine Aggregate Size	Less than 4.75 mm
W/C	0.33
Ratio	1:1.63:2.76:.33 (Cement: FA: CA: Water)
Admixture	3.44 kg/m^3
Measured Slump	12.0 cm (120 mm) 3.85 cm (38.5 mm) for 0.25%

2.2 Specimen preparation

All types of concrete were cast in the same mixer machine and in specially designed steel molds. For compacting the concrete, a tamping rod was used. Tamping was done in three layers. 25 blows were given in each layer. The same mix ratio and w/c ratio were maintained for all kinds of concrete specimens, as shown in Figure 1 (d).

Table 2
Fiber details

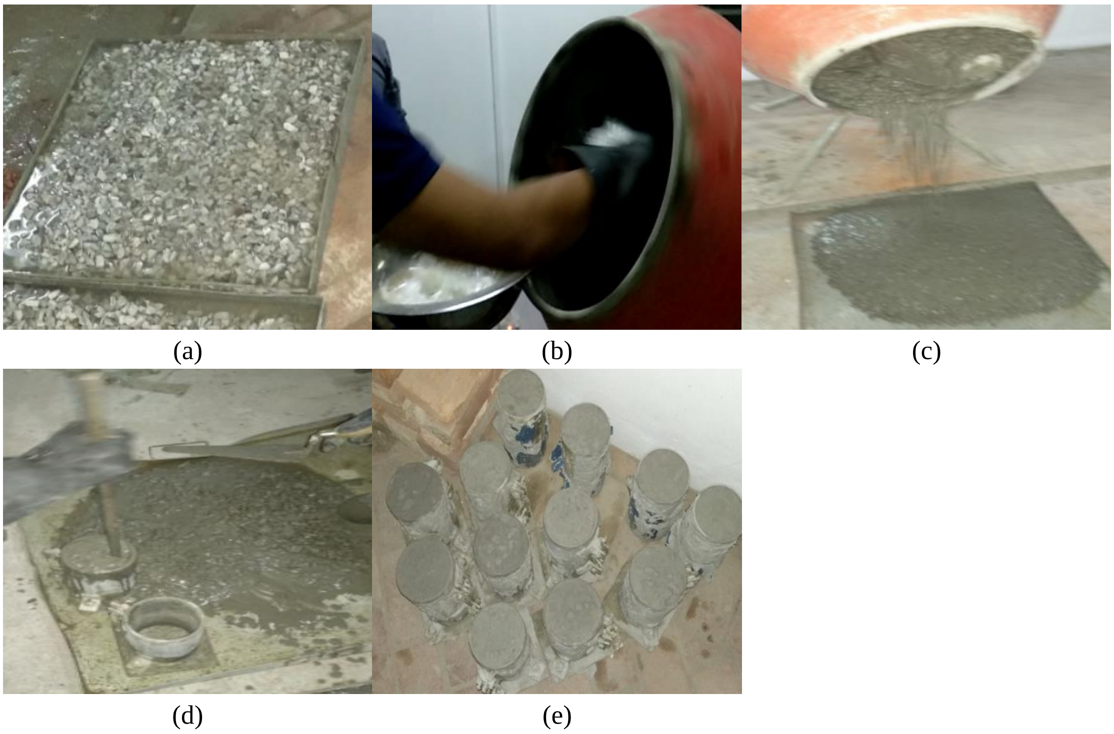
Parameter	Value
Fiber volume	0%, 0.25% and 0.5%
Fiber type	E-glass
Fiber tensile strength	3445 MPa
Fiber compressive strength	1080 MPa
Size	30 mm in length (approximately)

2.3 Curing of concrete

In this research, the samples were tested at 7, 14, and 28 days from casting, respectively, and the samples were cured for 7, 14, and 28 days, respectively, in the curing tank. They were completely submerged. Before testing, the cylinders were marked according to sequences Figure 2(a). In Figure 2(b and C), we can see the compression and tension tests of a concrete cylinder with the UTM machine. Figure 2 (d) illustrates the data collection pattern of the tensile test.

2.4 Data collection and analysis

A total of 48 concrete specimens underwent testing. This included 6 specimens without fiber for both compression and split tension, 9 specimens with 0.25% fiber for both compression and split tension, and 9 specimens with 0.5% fiber for both compression and split tension. A digital universal testing machine (UTM) was used at a consistent rate of 1.5 mm/min to apply load. The load cell recorded the applied loads, and the stress-strain curves were generated from this data. Lateral displacement during uniaxial compression was measured using a high-definition video camera and the Digital Image Correlation Technique (DICT). A synchronized data acquisition system combined load-displacement data from the UTM's load cell with strain measurements from image analysis.



(a) (b) (c)

(d) (e)

Fig. 1. Coarse aggregate b) mixing fiber in concrete c) concrete casting d) tamping concrete e) concrete molding in cylinder

3. Result and discussion

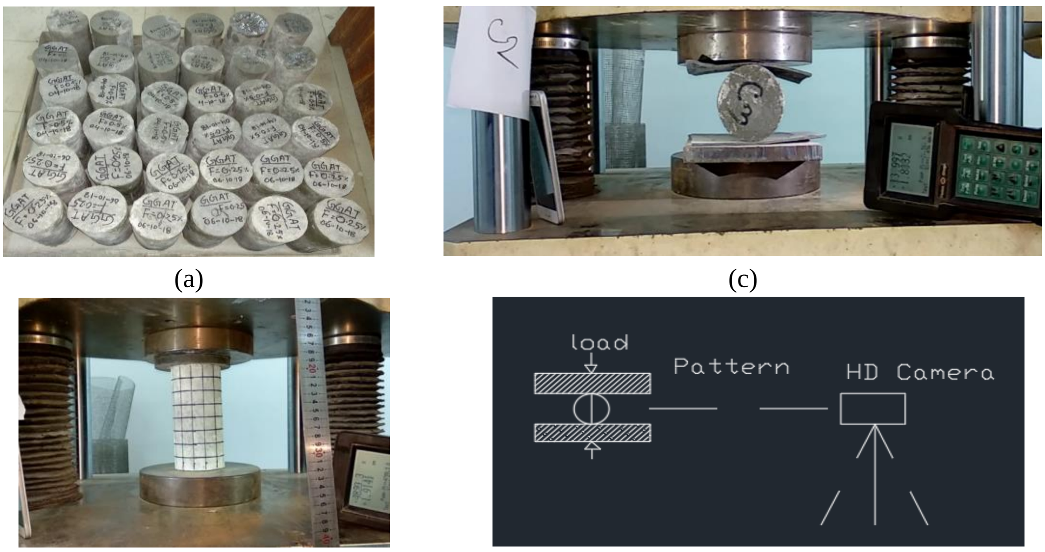
3.1 Effect of GFRC on concrete

3.1.1 Control specimen

In this study, compression tests on plain concrete control samples were performed 7, 14, and 28 days after casting. On separate days, distinct stress versus strain curves appeared (see Figure 3 a, b, and c). At 7, 14, and 28 days, respectively, the greatest compressive stresses for plain concrete were 4.65 MPa, 5.78 MPa, and 6.26 MPa. At the same time intervals, the highest compressive strains showed values of 0.024659993, 0.0066795358, and 0.0058847554. Notably, the strain witnessed a decrease with time whereas the compressive stress showed an increased tendency. For ordinary concrete, the highest tensile stresses measured at intervals of 7, 14, and 28 days were 1.05 MPa, 1.59 MPa, and 2.10 MPa. The highest tensile strains showed values of 0.05364043, 0.004364, and 0.005562186 at the same intersections. Figure 4 (a, b, and c) shows the corresponding trends. Notably, from 7 to 14 days, there was a rise in tensile stress and a parallel drop in strain. However, after 14 days, there is a noticeable increase in both tensile stress and strain.

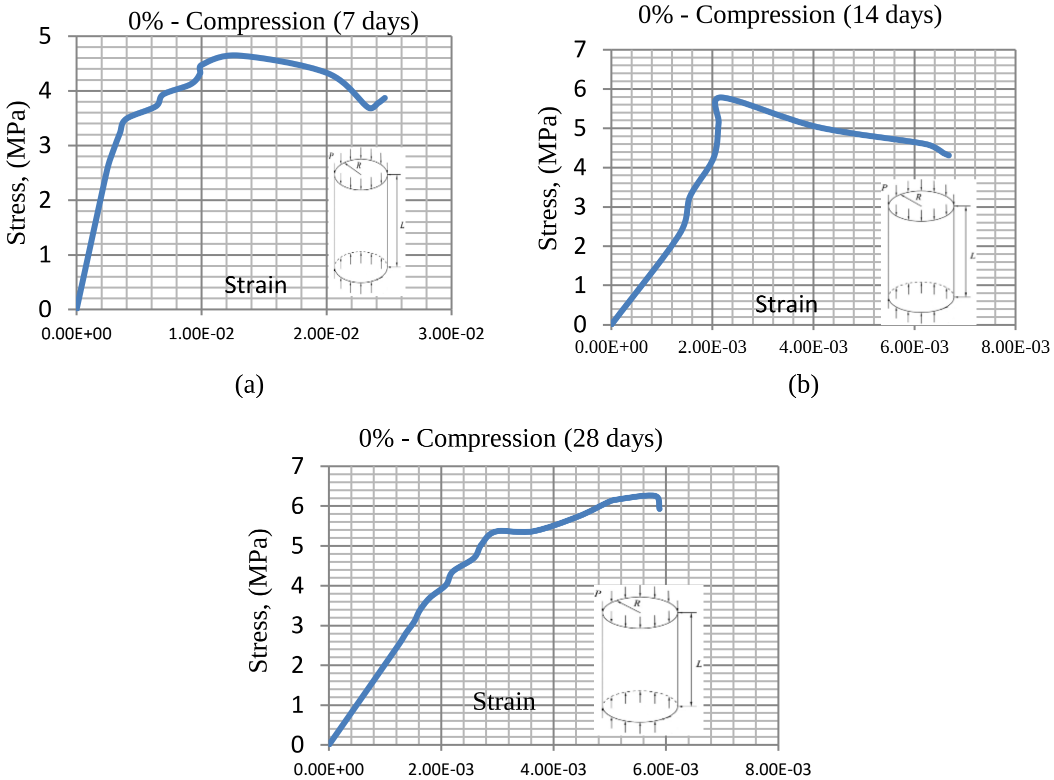
3.1.2 (0.25% fiber content) GFRC

For GFRC containing 0.25% fiber content, the compressive stresses stood at 6.80 MPa, 6.34 MPa, and 8.31 MPa after 7, 14, and 28 days, respectively. The pinnacle compressive strains recorded were 0.014836097, 0.0036587249, and 0.0095370069 over the same periods, as depicted in Figure 4 (d, e, and f). Notable patterns emerged: a rise in compressive stress occurred from the outset to day 7, followed by a decrease from 7 to 14 days. However, the zenith of compressive stress was attained at the 28-day mark. Correspondingly, the compressive strain witnessed a decline from 7 to 14 days, followed by a subsequent increase after 14 days. In the context of GFRC featuring 0.25% fiber content, the tensile stresses exhibited values of 1.28 MPa, 1.47 MPa, and 1.69 MPa across 7, 14, and 28 days, respectively. Simultaneously, the highest tensile strains registered were 0.005977, 0.018844, and 0.0116145 during the same periods, as portrayed in Figure 5 (a, b, and c). Notably, a discernible trend materialized: an augmentation in both tensile stress and strain was observed from day 7 to day 14, but a subsequent decrease occurred after the 14-day interval.



(a) (c) (b) (d)

Fig. 2. a) Concrete cylinder sample b) compression on cylinder c) split tension on cylinder d) horizontal data acquisition system concrete cylinder sample.



(c)

Fig. 3. a) Compressive stress-strain behavior of concrete (control, 7 days) b) compressive stress-strain behavior of concrete (control, 14 days) c) compressive stress-strain behavior of concrete (control, 28 days)

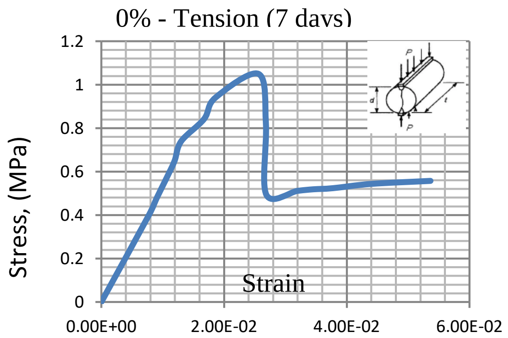
3.1.3 (0.5% fiber content) GFRC

In the context of GFRC featuring a 0.5% fiber composition, the compressive stresses demonstrated values of 6.31 MPa, 8.42 MPa, and 7.24 MPa at 7, 14, and 28 days, respectively. Concurrently, the maximum compressive strains reached extents of 0.016245598, 0.028438435, and 0.033379826 over the same periods, as illustrated in Figure 5 (d, e, and f).

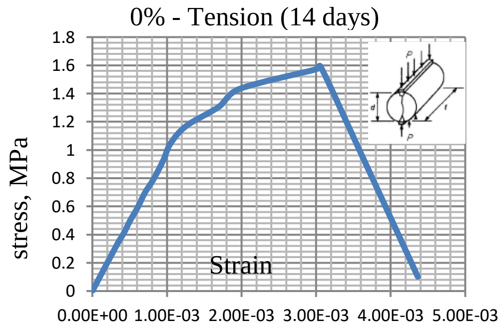
Notably, an observable pattern emerged: an ascent in compressive stress was noted from initiation to day 14, followed by a subsequent reduction from day 14 to day 28. Simultaneously, the compressive strain showcased an incremental trend as time progressed beyond the 14-day mark. In the context of GFRC incorporating 0.5% fiber content, the tensile stresses manifested as 1.18 MPa, 1.50 MPa, and 1.55 MPa over 7, 14, and 28 days, respectively. Concurrently, the maximum tensile strains were recorded as 0.009315, 0.0065123, and 0.001152, as depicted in Figure 6 (a, b, and c). A discernible trend emerged: there was a progressive increase in tensile stress juxtaposed with a corresponding decline in strain magnitude.

3.2 Combined analyses of compressive and tensile strength effect

Across 7 days in Figure 6 (d), higher fiber content led to increased strain, with peak compressive stresses at 4.65 MPa, 6.80 MPa, and 6.31 MPa for 0%, 0.25%, and 0.50% fiber content, respectively. Interestingly, 0.25% fiber content exhibited the highest stress. Within 14 days, as shown in Figure 6 (e), higher fiber content correlated with increased stress but reduced strain. Stresses were 5.78 MPa, 6.34 MPa, and 8.42 MPa for 0%, 0.25%, and 0.50% fiber content, respectively. At 28 days Figure 6 (f), higher fiber content was again linked to heightened strain, with peak compressive stresses at 6.26 MPa, 8.31 MPa, and 7.24 MPa for 0%, 0.25%, and 0.50% fiber content, respectively. Notably, 0.25% fiber content yielded the maximum compressive stress, decreasing beyond that level.



(a)



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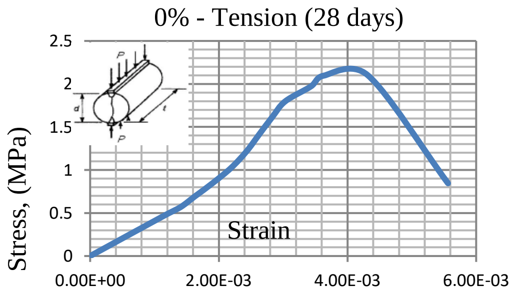

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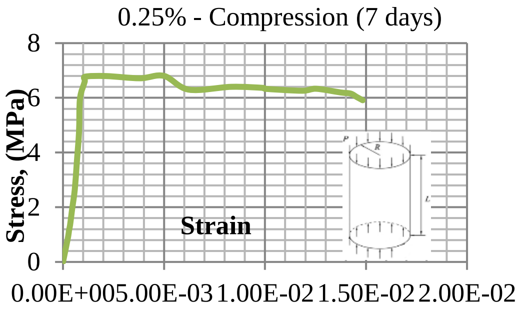
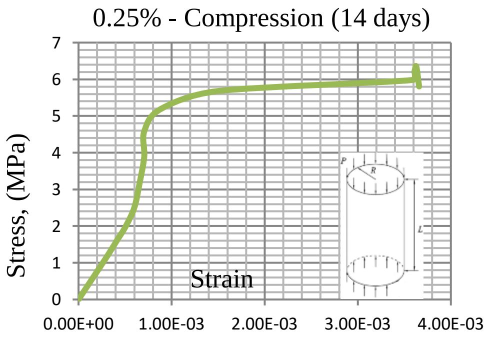
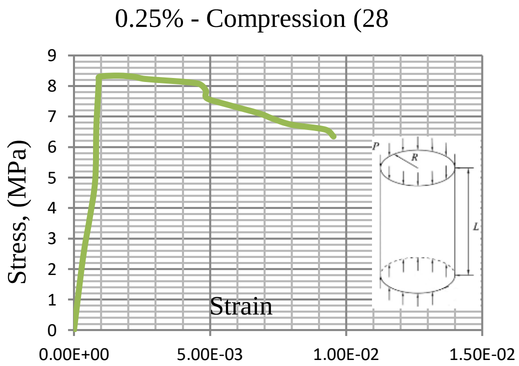


(d)



(e)



(f)

Fig. 4. a) Tensile stress-strain behavior of concrete (control, 7 days) b) tensile stress-strain behavior of concrete (control, 14 days) c) tensile stress-strain behavior of concrete (control, 28 days). d) compressive stress-strain behavior of concrete (0.25% fiber, 7 days) e) compressive stress-strain behavior of concrete (0.25% fiber, 14 days) f) compressive stress-strain behavior of concrete (0.25% fiber, 28 days)

3.3 Effect on tensile capacity (split tension)

In a 7-day span (Figure 7 (a)), increasing GFRC fiber content resulted in lower tensile strain, except beyond 0.25%, which led to higher strain. Maximum tensile stress was at 0.25%

GFRC, decreasing beyond that. At 14 days (Figure 7 (b)), above 0.25% GFRC, tensile strain decreased while stress increased. Notably, 0.25% GFRC showed the maximum tensile strain, while 0% GFRC exhibited the highest stress. By day 28 (Figure 7 (c)), elevated GFRC fiber content correlated with reduced tensile stress. Interestingly, 0.25% GFRC had the highest tensile strain, which decreased above that level.

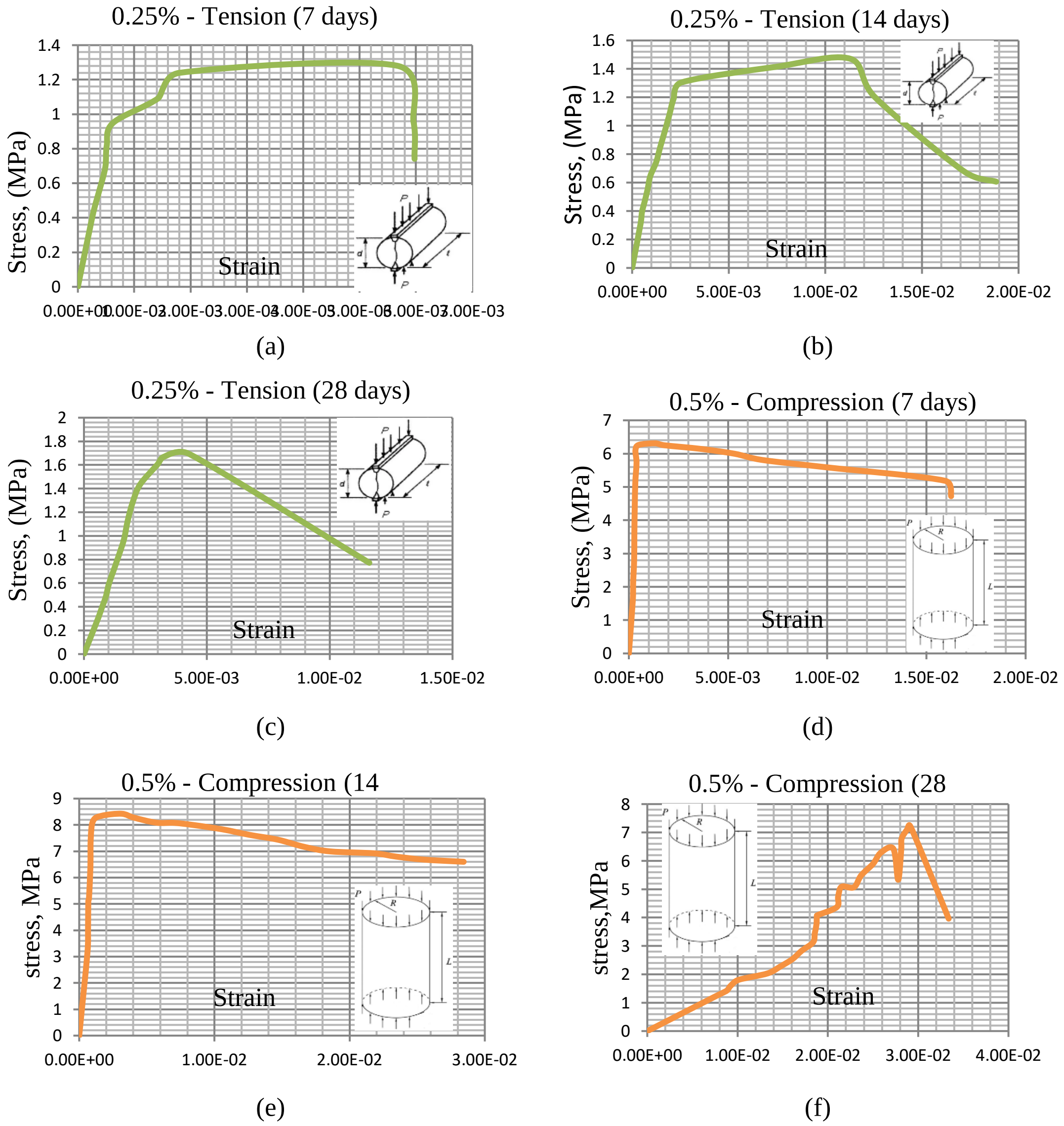
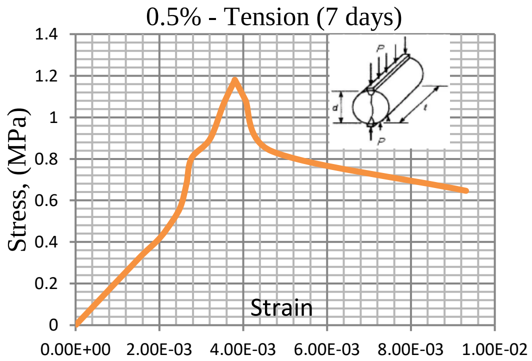


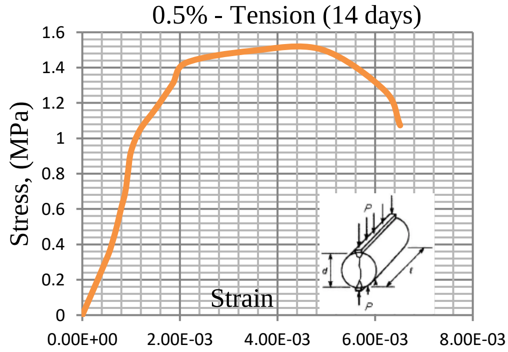
Fig. 5. a) Tensile stress-strain behavior of concrete (0.25% fiber, 7 days) b) Tensile stress-strain behavior of concrete (0.25% fiber, 14 days) c) Tensile stress-strain behavior of concrete (0.25% fiber, 28 days) d) Compressive stress-strain behavior of concrete (0.5% fiber, 28 days)

3.4 Failure pattern analysis

Concrete, initially strong in compression but weak in tension due to crack formation, gains tensile strength through reinforcement like bars and fibers. Despite its brittle appearance, concrete is a quasi-brittle material with non-linear behavior, deriving hardness from subcritical cracking during loading and featuring a complex, heterogeneous structure. A list of failure patterns is illustrated in Figure 8. Table 3 concludes the comparison of failure patterns between experiments and the finite element model.



(a)



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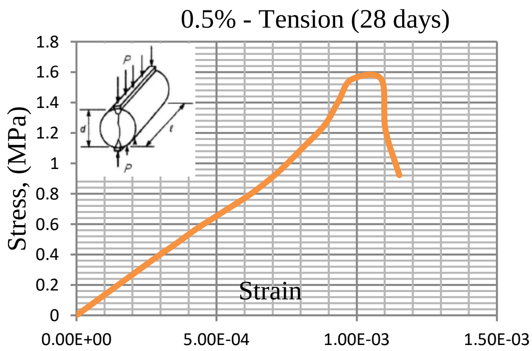

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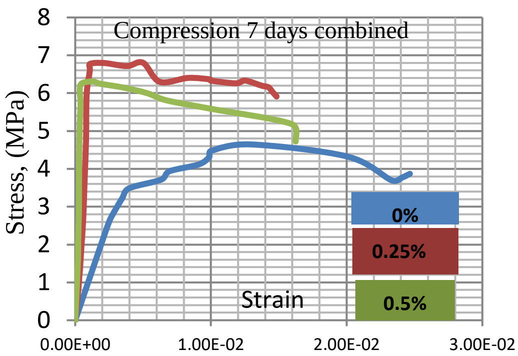
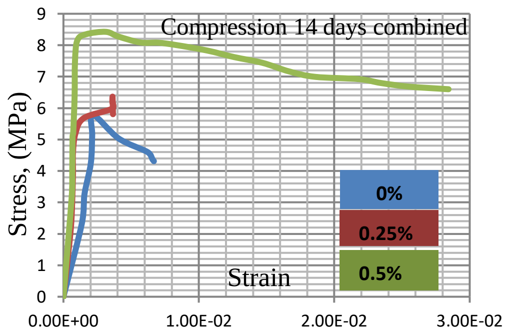


(d)



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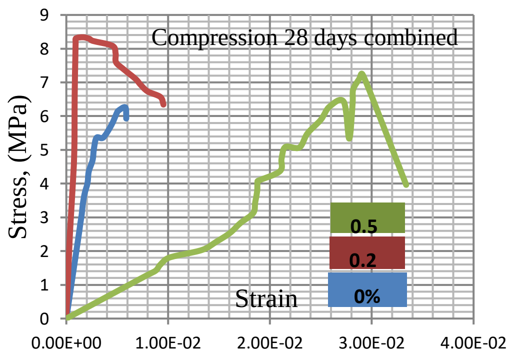


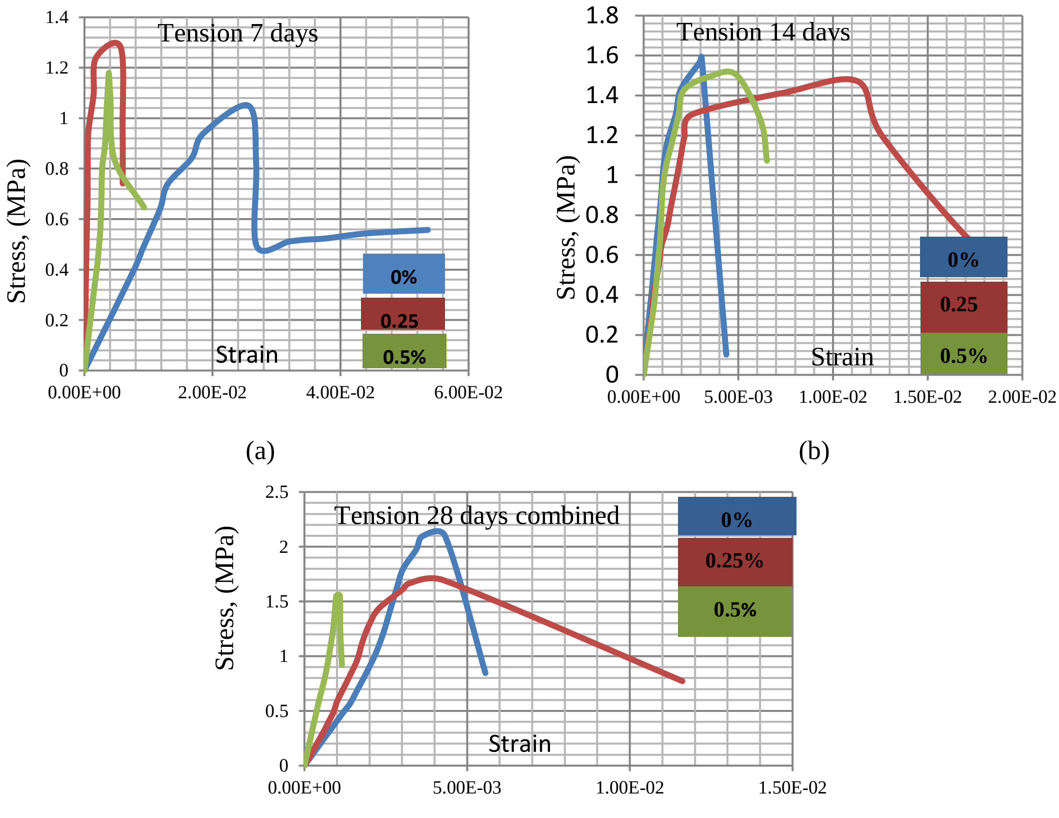
(f)

Fig. 6. a) Tensile stress-strain behavior of concrete (0.5% fiber, 7 days) b) Tensile stress-strain behavior of concrete (0.5% fiber, 14 days) c) Tensile stress-strain behavior of concrete (0.5% fiber, 28 days) d) Compressive stress-strain behavior of concrete (0%, 0.25%, 0.5% fiber, 7 days) e) Compressive stress-strain behavior of concrete (0%, 0.25%, 0.5% fiber, 14 days) f) Compressive stress-strain behavior of concrete (0%, 0.25%, 0.5% fiber, 28 days)

4. Conclusions and recommendations

4.1 General

This research investigates the impact of adding glass fibers to concrete, aiming to enhance its properties. Despite some prior use of glass fibers as a steel substitute, few studies have examined the compressive and tensile strengths of GFRC cylinders with varying fiber combinations. The study evaluates 36 specimens to understand capacity enhancement and stress distribution in GFRC, considering fiber availability in Bangladesh.



(c)

Fig. 7. a) Tensile stress-strain behavior of concrete (0%, 0.25%, 0.5% fiber, 7 days) b) tensile stress-strain behavior of concrete (0%, 0.25%, 0.5% fiber, 14 days) c) tensile stress-strain behavior of concrete (0%, 0.25%, 0.5% fiber, 28 days)

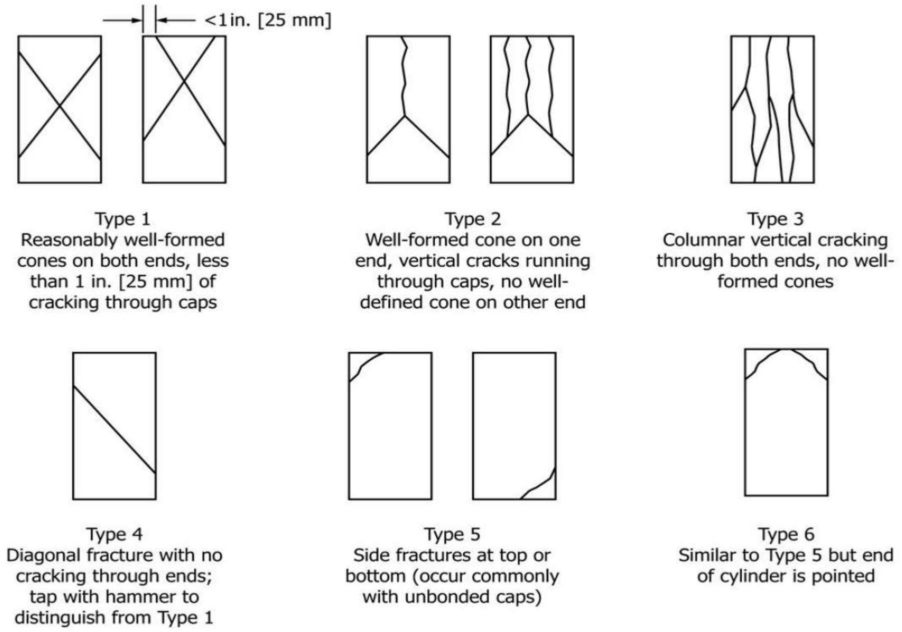


Fig. 8. Types of failure pattern.

Table 3
Comparison of failure pattern between experiment and finite element model

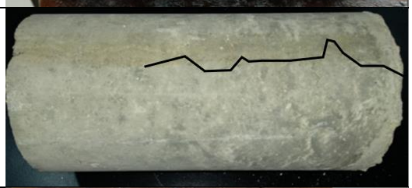
Sl. No.	Percent of Fiber	Types of Tests	Types of Failure	Day	Failure Patterns
1	0%	Compression	Type-2	7	
2	0%	Compression	Type-2	14	
3	0%	Compression	Type-5	28	
4	0%	Tension	Type-3	7	
5	0%	Tension	Type-3	14	
6	0%	Tension	Type-3	28	
7	0.25%	Compression	Type-2	7	
8	0.25%	Compression	Type-2	14	
9	0.25%	Compression	Type-2	28	

Table 3 (cont.)
Comparison of failure pattern between experiment and finite element model

Sl. No.	Percent of Fiber	Types of Tests	Types of Failure	Day	Failure Patterns
10	0.25%	Tension	Type-2	7	
11	0.25%	Tension	Type-3	14	
12	0.25%	Tension	Type-2	28	
13	0.50%	Compression	Type-2	7	
14	0.50%	Compression	Type-5	14	
15	0.50%	Compression	Type-5	28	
16	0.50%	Tension	Type-4	7	
17	0.50%	Tension	Type-2	14	
18	0.50%	Tension	Type-2	28	

4.2 Conclusions

1. GFRC Strength at 0.25% Glass Fiber vs. 0% Glass Fiber:
- Workability unaffected.
- Max tensile strength at 0.25% fiber after 28 days. Increases by 23.24% at 7 days, decreases by 21.42% at 14 days, and increases by 18% at 28 days.
- Max compressive strength at 0.25% fiber after 28 days. Increases by 28.27% at 7 days, 23.15% at 14 days, and 30.92% at 28 days.
2. GFRC Strength at 0.5% Glass Fiber vs. 0% Glass Fiber:
- Higher fiber affects workability.
- Max tensile strength at 0.5% fiber after 28 days. Increases by 13.78% at 7 days, decreases by 4.93% at 14 days, and increases by 25.52% at 28 days.
- Max compressive strength at 0.25% fiber after 14 days. Increases by 27.88% at 7 days, 49.96% at 14 days, and 26.1% at 28 days.
3. Comparing GFRC strength (0.25% vs. 0.50% glass fiber):
- Workability: Concrete is more workable with 0.25% glass fiber.
- Tensile Strength: At 28 days, 0.25% glass fiber exhibits 10.08% higher tensile strength compared to 0.50% glass fiber. At 7 days, the difference is 8.31%, and at 14 days, it's 1.63%.
- Compressive Strength: At 14 days, 0.50% glass fiber achieves a maximum compressive strength that's 26.08% higher than 0.25% glass fiber. At 28 days, the difference is 4.82%.

4.3 Recommendations

For future studies, it is recommended to:

1. Varied Fiber Length Investigation: The exploration of diverse fiber lengths, extending beyond the established 30 mm, would enable a nuanced understanding of their implications for crack resistance, ultimate strength, and post-crack deformation characteristics.
2. Fiber Dispersion Analysis: A thorough examination of fiber alignment within the concrete matrix is warranted to elucidate its influence on crack propagation dynamics.
3. Comparative Fiber Assessment: Conducting a comparative analysis encompassing steel, synthetic, and glass fibers would provide valuable insights into their distinctive roles in enhancing concrete properties.
4. Durability Under Duress: A comprehensive assessment of fiber-reinforced concrete's long-term performance under challenging environmental conditions, including freeze-thaw cycles and chemical exposures, is essential.
5. Real-world Structural Application: The application of fiber-reinforced concrete within authentic structural components, such as beams and columns, offers practical insights into its performance in real construction scenarios.
6. Optimal Fiber Content Determination: By meticulously investigating a broader spectrum of fiber percentages, the identification of the optimum content for maximal crack resistance, strength, and deformation behavior can be achieved.
7. Synergistic Reinforcement Study: An exploration of the synergistic effects arising from the integration of glass and steel fibers would yield valuable insights into their combined impact on crack control and deformation response.
8. Numerical Validation and Verification: Employing numerical simulations and finite element analysis to validate experimental findings would establish a robust foundation for comprehending concrete behavior across diverse loading conditions.
9. Empirical Validation in Real-world Settings: The validation of research outcomes through empirical validation within actual construction projects would provide tangible evidence of fiber-reinforced concrete's efficacy.

10. Economic Feasibility Evaluation: A meticulous economic analysis encompassing material costs, construction techniques, and long-term maintenance considerations would offer insights into the economic viability of widespread glass fiber-reinforced concrete adoption.

These recommendations, when judiciously implemented, are poised to yield valuable insights, contributing to informed decision-making within the construction domain.

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