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Research Article

Flexural behavior of GFRP rebars and steel rebars with polypropylene fibers and fly ash-based concrete

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Abstract

Alternative materials are required since steel reinforcement in concrete constructions is prone to rust, which creates durability issues. This study investigates the feasibility of replacing steel reinforcement in concrete applications with glass fiber-reinforced polymer (GFRP) rebars. The experimental work used M30 grade concrete with two mix designs: fiber-reinforced concrete (FA+PP), which replaces cement with 20% fly ash, and nominal concrete (NC), which uses 1% polypropylene fiber. Both mixes met M30 standards,FA+PP showed higher strength. Four steel or GFRP reinforced concrete beams sized as 1500 mm × 230 mm×300 mm underwent flexural loading tests. The period for NC beam curing amounted to 28 days but FA+PP beams received 56 days of treatment before testing. The experimental results demonstrated that steel-reinforced beams made with FA+PP produced the highest resistance against loading force alongside minimal beam movement yet FA+PP beams using GFRP bars displayed an average strength level together with continuous flexural deflection. Structural specimens reinforced using steel demonstrated superior results than specimens made of GFRP and NC materials during load-bearing examination. GFRP rebars demonstrate value as steel reinforcement replacement because they provide corrosion protection and structural strength according to this research finding.

1.Introduction

Construction project design requirements and service life depend directly on the behavior of concrete-reinforced beams during flexure. Traditional steel reinforcement serves as a standard building material due to its combination of strength attributes together with ductility properties since decades. The usage of fiber-reinforced polymer (FRP) rebars [1] as construction alternatives materialized because engineers wanted to overcome material sustainability issues along with corrosion protection limitations. The scientific community adopted GFRP rebars as steel replacements [2] because they provide lightweight material strength while exhibiting high durability against corrosion. Structural concrete performances improve when fly ash serves as cementitious material and incorporates polypropylene fibers into it. This paper examines steel

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rebar flexural behavior studies and GFRP-reinforced concrete beam research while analyzing the improvement effects of fly ash and polypropylene fibers on concrete material properties. [3-7].

The construction industry uses steel rebars as its standard reinforcement material because engineers understand their behavior and they have high strength for bending actions. Industrial applications of steel reinforcement experience corrosion that generates both structural deterioration and expenses for maintenance (ACI 440.1R-15, 2015) [8]. The corrosion-resistant nature of GFRP rebars makes them the optimal choice for structures located in salty water or bridge conditions based on research presented in references [9-11]. Consequently, researchers have looked for alternative means of steel reinforcement since there is rising demand for sustainable construction practices. High tensile strength to weight ratio and non-conducting properties have emerged which advantageous over other rebars like corrosion resistance and marine environment. However, despite their structural behavior which is different from steel, their evaluation must be discussed systematically.

The flexural behavior of concrete beams which use steel in combination with GFRP has been measured through experimental studies. Service load deflections from beams reinforced with GFRP yielded elevations over steel-reinforced beams according to Benmokrane et al. [1]. The results of Zhang et al. [12] support observations about GFRP-reinforced beams which display decreased stiffness because of their elastic modulus but maintain acceptable load-load capacity. GFRP reinforcement shows its main disadvantage through its characteristic brittleness which leads to sudden failure. GFRP rebar is also known as Pseudo ductile material. GFRP shows a different failure behavior by breaking instantly through fiber rupture instead of yielding like steel does before failure occurs. Seamless ductility enhancement of GFRP-reinforced beams occurs with optimized reinforcement ratios combined with steel reinforcement according to El-Gamal et al. [13].

Concrete builders extensively use polypropylene fibers because they enhance tensile strength and provide impact resistance together with crack control capability. The study conducted by Alhozaimy et al. [14] proved that concrete becomes less brittle after adding polypropylene fibers through their role as microcrack bridge elements that slow down the spread of cracks. Fiber reinforcement enables concrete to absorb more energy along with improving its toughness because of which it exhibits greater resilience to impact and cyclic loading [15-16]. The flexural properties of concrete beams under examination by Sivakumar and Santhanam [17] depended on the polypropylene fiber volume percentage. The researchers discovered that adding 1% fibers resulted in the maximum toughness enhancement while maintaining workability at optimal levels. The research of Karthik et al. [19] revealed that concrete beams became tougher and developed better ductility upon addition of polypropylene fibers while maintaining quality workability metrics.

Research conducted by Nili and Afroughsabet [20] demonstrates that fiber-reinforced concrete maintains increased strength after the load peak and this feature enhances the structural behavior of GFRP-reinforced members. Workability problems and unreliable fiber distribution may occur because of high fiber content so mix design requires proper proportioning. Fly ash serves as a frequently employed supplementary cementitious material to replace Portland cement in concrete because it stems from coal burning operations. Fly ash delivers numerous advantages to concrete through improved durability as well as better workability combined with lower heat of hydration and stronger long-term strength according to Mehta and Monteiro [21-22]. According to Thomas and Matthews [23] replacing 20-30% of cement with fly ash produces maximum strengths in both compressive and flexural tests on concrete. According to Malhotra [24], fly ash improves both sulfate resistance and lowers permeability, allowing it to function effectively in oceanic and corrosive environments. The sustainable benefits of fly ash arise from its ability to decrease cement production emissions during manufacturing.

The use of polypropylene fibers with fly ash-based concrete produces combined advantages. Chidambaram et al. [25] showed that polypropylene fibers make up for the strength decline caused by fly ash in early concrete development and fly ash extends concrete lifetime expectancy. The simultaneous use of fly ash together with fiber reinforcement offers a practical approach to strengthen concrete durability as well as its mechanical elements. Research investigates the use of GFRP rebars in flexural areas next to steel stirrups in shear regions to maximize advantages from each reinforcement type. The implementation of steel stirrups in GFRP-reinforced beams demonstrated according to Ali et al. [26] that steel stirrups enhance shear resistance and stop sudden structural failures. This combined approach provides excellent shear reinforcement through steel bars and extends GFRP's corrosion-resistant properties within flexural areas. According to Nanni et al. [27] a beam benefits from its combined GFRP longitudinal reinforcement and steel stirrups because these elements establish an efficient load redistribution system which improves structural performance. Hybrid reinforcement methods find practical use in aggressive settings because they address primary concerns regarding corrosion resistance. Also, partial substitution of cement with industrial by product such as fly ash did not only reduce the carbon footprint but also has some advantages of mechanical property and long-term durability. Under flexural loading, crack resistance, improved toughness and energy absorption have been contributed by the inclusion of polypropylene fibers. Thus, combining these materials offers a synergistic method towards sustainable and durable concrete components with good structural stiffness.

Research on GFRP reinforcement, polypropylene fibers and fly ash extends throughout concrete beams flexural performance but combined implementation still lacks significant investigation. Current research exists separately as steel vs. GFRP reinforcement investigations or studies on fiber-reinforced concrete without assessing multiple components together within one structural framework. Strengthening infrastructure durability requires studies of multifactor effects between GFRP rebars and polypropylene fibers and fly ash-based concrete for flexural strength assessment since infrastructure demands will continue to grow. The present research gap receives resolution through comprehensive laboratory testing of concrete beams containing these materials. The researched information about load-deflection behavior alongside failure mechanisms and cracking patterns generated new understanding to develop improved structural systems which resist corrosion. Through systematic research both present standards can improve, and scientists gain essential data for deploying hybrid reinforcement systems under various environmental conditions for long-term performance.

1.1 Purpose and Objectives of the Study

This study is primarily concerned with experimental evaluation of flexural performance of concrete beams with Glass fiber reinforced polymer (GFRP) rebars as opposed to conventional steel rebars. For the purpose of improving the sustainability and mechanical properties of concrete, a hybrid mix of 20% fly ash as partial cement replacement and 1% polypropylene fibers by volume was employed.

The study seeks to achieve the following specific objectives.

- An investigation on the effects of replacing steel rebars with GFRP rebars as an alternative choice in reduced strength reinforced concrete beams under flexural load was conducted.
- It is necessary to evaluate mechanical performance of the normal as well as fiber reinforced concrete with GFRP and steel reinforcements (load vs. deflection).
- A systematic assessment of GFRP rebars viability as a structural concrete application with industrial by products (fly ash) and synthetic fibers (polypropylene) from a sustainability as well as strength improvement perspective.

This study helps to build the body of knowledge about advanced composite reinforcement for eco efficient systems by addressing the combined effects of the various modifiers as well as alternative reinforcement.

2. Experimental Program

2.1. Materials And Properties of Materials

The materials used in the experimental program are characterized to illustrate the following instances.

2.1.1 GFRP Rebar and Steel Rebar

The steel bars used in the longitudinal and stirrup bars for the beam were 10mm FE 550 for top longitudinal reinforcement and 12mm steel bars for bottom longitudinal reinforcement and 8mm steel bars for the stirrup bars respectively. GFRP Rebars of 12mm were used as top and bottom longitudinal reinforcement and 8mm steel bars are used as shear reinforcement. The test results of the GFRP and FE 550 steel bars in terms of mechanical properties are shown in Table 1. It should be also stated that the mechanical performance specifications for the steel and GFRP bars were offered by the material supplier.

Fig. 1. GFRP rebar and steel rebar

Table 1. Rebar properties

Rebar Type	Tensile Strength (MPa)	Elastic Modulus (GPa)	Ultimate Strain (%)	Shear Strength (MPa)	Density (g/cm^3)	Poisson's Ratio	Thermal Expansion (µm/m°C)
12mmϕ GFRP	920	46.59	3.5	72.55	2.06	0.28	35
12mmϕ STEEL	550	200	13	460	7.85	0.3	13

2.1.2 Cement

The IS 269:2015 [28] compliance is achieved through using OPC 53 grade cement of good quality and locally available material.

2.1.3 Fly Ash

Industries that produce fly ash byproducts leave behind ashes, rich in alumina, silica and ferric oxide, when coal is heated at high temperatures in thermal power plants. Fly ash (FA) is used in the concrete to improve workability, to reduce heat of hydration and is resistant to extremely chemical attacks. The class F type Fly ash is used as binder material replacing 20% cement in the experiment.

Table 2. Properties of Binding Materials

Material	Specific gravity	Standard consistency (%)	Initial setting time (Minutes)	Final setting time (Minutes)	Bulk density (kg/m^3)
Cement	3.14	32	40 min	10 hours 600	1440
Fly Ash	2.2	30	55 min	12 hours 720	1100

2.1.4 Coarse Aggregate

The size of the coarse aggregate employed for casting, as specified in IS 383:1970, varies between 20 mm with a specific gravity of 2.74 [29]. We use the mixture which contains 100% of 20 mm in weight. Table 3 displays the results of the preliminary test.

2.1.5 Fine Aggregate

Fine aggregates were used from uncrushed, locally occurring local river sand ~~having a maximum~~ passing through sieve size of 4.75 mm, ~~a~~ fineness modulus of 3.35 and a specific gravity of 2.65 need to be attained as per IS 383:1970. Table 3 displays the results of the preliminary test.

Table 3. Properties of aggregates

Material	Density (kg/m^3)	Water Absoprtion (%)	Fineness modulus	Max Dia (mm)	Zone	Specific gravity
Fine Aggregate	3.14	2.1	3.23	-	II	2.67
Coarse Aggregate	2.2	0.43	3.18	20	-	2.89

2.1.6 Tap Water

Mixing and curing was done with Ordinary Potable tap water.

2.1.7 Super Plasticizer

A high range water reducing agent (water reducers) with specific gravity of 1.11, having a chemical admixture complying to IS: 9103:1999 [30] was used; this water reducer was used as HYPERFLUID R200 for the purpose of increasing the workability as well as the strength of concrete. Specifications of superplasticizer are shown in Table.4

Table 4. Properties of super plasticizer

S.no	Parameter	Specifications
1	Appearance	Yellowish brown liquid
2	Base material	Poly carboxylic ether
3	Specific gravity	1.11
4	Ph	6.7
5	Solid content	41
6	Chloride content	Nil

2.1.8 Polypropylene Fiber

Polypropylene fibers are added to the concrete mixtures in order to improve some of the key performance parameters. The most important of their properties is to help enhance impact resistance, mitigate plastic shrinkage cracking and improve long term durability of the concrete matrix. No, these discontinuous, uniformly dispersed fibers are not to be significant on the compressive strength, but they are greatly beneficial to post cracking behavior by increasing toughness, energy absorption, and crack bridging capacity.

Table 5. Specifications of polypropylene fiber

S.no	Parameter	Specifications
1	Length	20mm
2	Diameter	19-40 micron
3	Aspect ratio	215-1250
4	Specific gravity	0.91
5	Melting point	162°C
6	Ignition point	360°C
7	Thermal conductivity	Low
8	Alkali resistance	Low

Fig. 2. Polypropylene fiber

The structural integrity of this fiber reinforced concrete is enhanced due to the presence of this reinforcement fiberization mechanism, therefore polypropylene fibers can be used as an additive in the performance oriented and durable concrete applications.

2.1.7 Mix Design

Concrete mix design was performed by using IS 456-2000 [32] and IS 10262-2019 [31]. ~~The~~ M30 concrete grade is mixed, and the weight ratio is determined. A water reducing agent (superplasticizer) is utilized and this is given in Table 6. 20% of Fly Ash has been replaced in cement for FA+PP mix. Nomenclature for concrete mix designs is given as NC – Nominal Concrete, FA+PP – Fly Ash + Polypropylene Fiber Concrete

Table 6. Material proportions for concrete

Mix ID	Cement	Fly Ash	Water	Fine Aggregates	Coarse Aggregates	Chemical Admixture	Fiber
NC	352	-	158	704.98	1213.96	1.056	-
FA+PP	280.88	70.22	158	695.76	1198.08	1.4	9

Material Proportions given in the above table are calculated for Kg/m³

3. Experimental Program

3.1. Materials And Material Properties

Conventional size cube specimens (0.15 m × 0.15 m × 0.15 m) are cast for every curing phase. After mixing two concrete recipes, the cubes are stored for curing. With Compressive Testing Machine (CTM) dried specimens are placed for the curing of 7, 14, 28 & 56 days. Fig. shows the samples being tested and prepared. IS 516[33] recommends the normal loading rate at which the concrete compressive strength is tested at a rate of 14 MPa per minute for cubes.

Fig. 3. Compressive strength test setup

3.2. Flexural Studies of RC Beams

Four reinforced concrete beams were cast and tested to investigate the load vs. deflection behavior in this study. All the beams were sized 1500 mm×230 mm×300 mm. Based on the concrete mix and testing conditions, the beams were placed into two groups:

- Nominal Concrete (NC):

M30 Nominal Concrete (NC), which RC beams were reinforced with GFRP and steel rebars that are allowed to cure for 28 days, was used to cast two RC beams.

- Replaced Concrete (FA+PPF):

M30 concrete was used to cast two beams, with Fly Ash replacing 20% of the cement and 1% of polypropylene fibers. Reinforcement was given by GFRP and steel rebars, which were allowed to cure for 56 days.

Table 7. Specification of Beam Types and Identification Codes

Specification	Beam ID
Beam with GFRP as internal reinforcement for NC	NC-G
Beam with STEEL as internal reinforcement for NC	NC-S
Beam with GFRP as internal reinforcement for FA+PPF	FA+PPF-G
Beam with STEEL as internal reinforcement for FA+PPF	FA+PPF-S

3.3. Reinforcement Details

- Each beam was reinforced as follows:

The beams reinforcing details included for shear resistance, 8 mm diameter stirrups are used as transverse reinforcement, To effectively resist tensile stresses induced under flexure loading 12 mm diameter rebars are used as bottom longitudinal reinforcement, and to provide necessary compression and enhance ductility and crack control capacity under the reversed or negative moment zones steel bars with 10 mm diameter rebars are used as top longitudinal reinforcement..

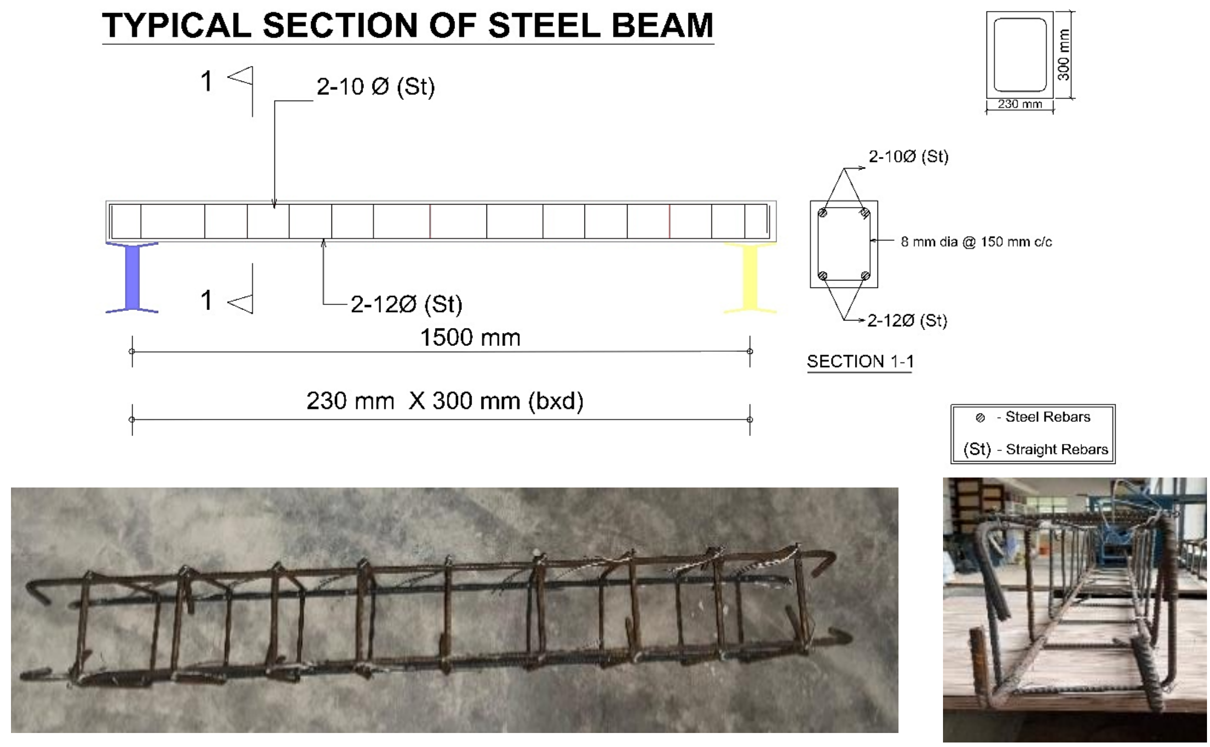


Fig. 4. Reinforcement detail of Steel beam

The structural performance under service and ultimate conditions was balanced through a strategic design of this reinforcement configuration. For the alternative reinforcement setup to structure, 12 mm diameter GFRP rebars were used symmetrically for both the top and bottom longitudinal reinforcement to create balanced flexural capacity at the bottom. Top of the beam specimens and strength to improve the tensile strength and control deflection under service loads, strategically embedded at the center of the two bottom longitudinal reinforcement layers, a single 12 mm diameter steel rebar was used, while 8 mm diameter mild steel rebars were used as transverse support in the form of stirrups to provide shear resistance that was uniformly distributed along the span to confine the concrete core and prevent the diagonal tension failureIn this hybrid reinforcement approach, a low modulus of elasticity of GFRP is compensated with steel reinforcement in order to release the structural stiffness, while using the corrosion resistance and high tensile strength-to-weight ratio of GFRP bars.

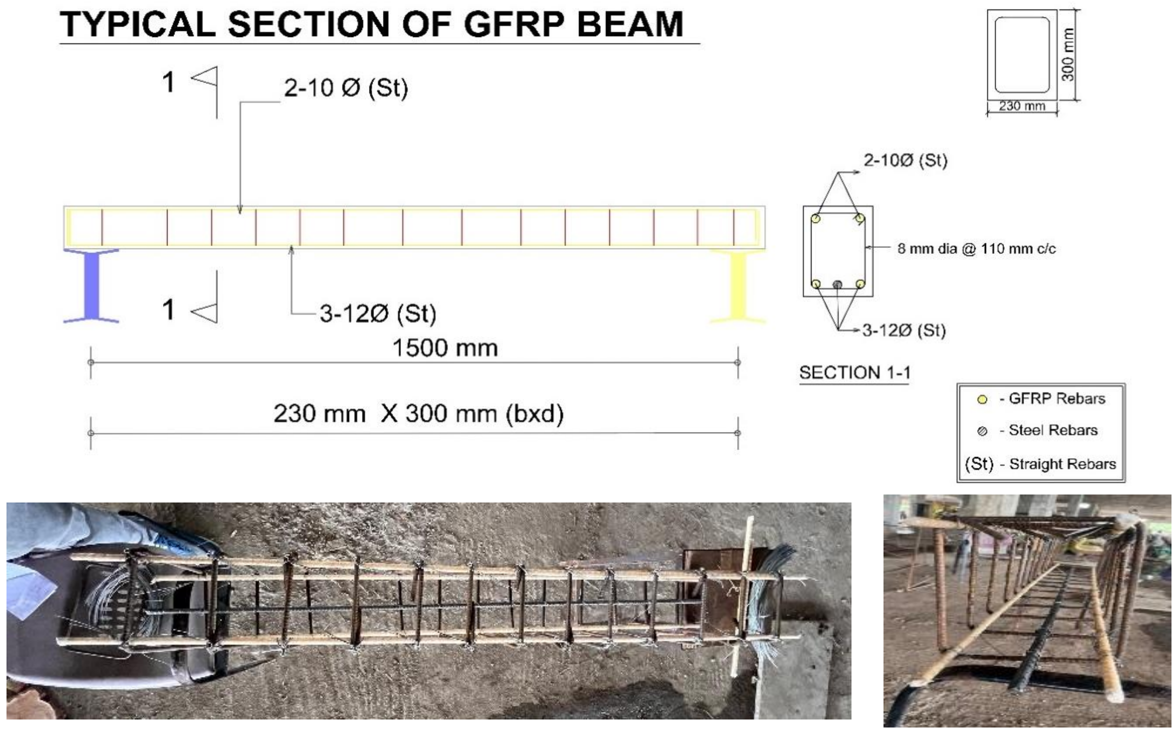


Fig. 5. Reinforcement detail of GFRP beam

3.4. Reinforcement Preparation

Rigid steel plates were fabricated to make the beam molds with dimensional stability and to prevent slurry leakage during casting. The inner surfaces were then coated uniformly with a coating release agent to promote smooth demolding before placement of concrete. Three successive layers of concrete mix, placed with the aid of a mechanical mixer to ensure homogeneity, were made. The compaction of each layer was also ensured by thoroughly compacting the entrapped air and ensuring proper consolidation using a mechanical vibrator. The beams were set up for 24 hours and carefully demolded after which membrane curing was done using moist gunny bags in order to maintain adequate surface hydration and attain optimum strength development.

(a) (b)

(c)

(d)

Fig. 6. Step-by-step casting procedure of reinforced concrete beam specimens (a) preparation of mold (b) placement of reinforcement (c) wet concrete in mold and (d) membrane curing

3.5. Testing Procedure of Beam

A loading frame with a two-point loading mechanism was used to characterize all four beams: NC-S, NC-G, FA+PP-S, and FA+PP-G. The supports and loading points had equal distance between them because the load was distributed symmetrically. To evaluate the flexural behavior of the beams, the load vs. deflection data was recorded at regular intervals after loading until failure. The characterization of the effect of reinforcement type (GFRP vs. steel), fly ash replacement (20%), and polypropylene fiber (1%) on the structural performance of the beam was made by this testing procedure. These findings deepen understanding of the influence of fiber reinforcement and additional cementitious materials on failure characteristics, stiffness, and flexural capacity.

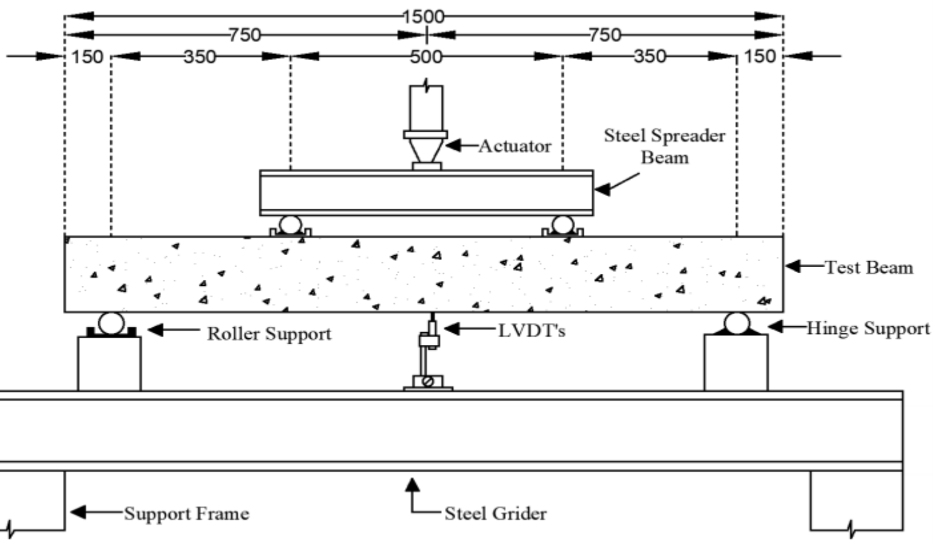


Fig. 7. Sketch of experimental setup

4. Results and Discussions

4.1. Compressive Strength

Specific trends in the development of the compressive strength were observed for the Normal Concrete (NC) mix and the Fly Ash with Polypropylene Fiber (FA+PP) modified concrete mix as they result from dissimilar hydration and pozzolanic reaction kinetics. The compressive strength at an early age for the NC mix was measured to be 18.22 MPa at 7 days, 24.19 MPa at 14 days, and 40.65 MPa at 28 days. Mildly continuous improvement of strength was noted, again achieving 44.85 MPa at 56 days which increased by 10.34% from 28 to 56 days, implying conventional hydration maturity. On the contrary, FA+PP mix showed relatively lower early age strengths of 16.18 MPa and 22.55 MPa at age 7 and 14 respectively, which are around 11.2 % and 6.8 % lower than the NC mix at the same ages. But beyond 28 days, there was a marked shift in the development of strength. The compressive strength of the FA+PP mix at 28 days was 30.28 MPa (25.5% lower than the NC mix at the same age), however the strength gain accelerated fast from 28 days to 56 days resulting in a compressive strength of 54.28 MPa at 56 days. 78.5% higher than 28 days strength and, still relatively, far beyond the NC mix by about 21% at 56 days.

Table 8. Compressive strength test results for NM and FA+PP mixes at different curing ages

Days	Nominal Concrete (NC)	FA+PP
7	18.22	16.18
14	24.19	22.55
28	40.65	30.28
56	44.85	54.28

Results show that the results are characteristic in fly ash-based systems because the pozzolanic reaction is slow and becomes more accentuated beyond 28 days of curing time. In addition, the long-term strength was likely for the one with polypropylene fibers since it enhanced crack-bridging capacity and microstructural integrity. FA+PP mix shows improved 56-day performance over the other mixes, which demonstrates its potential for use in structural applications focusing around higher final strength gain, long term durability and utilization of material over its service life where early age strength is less important.

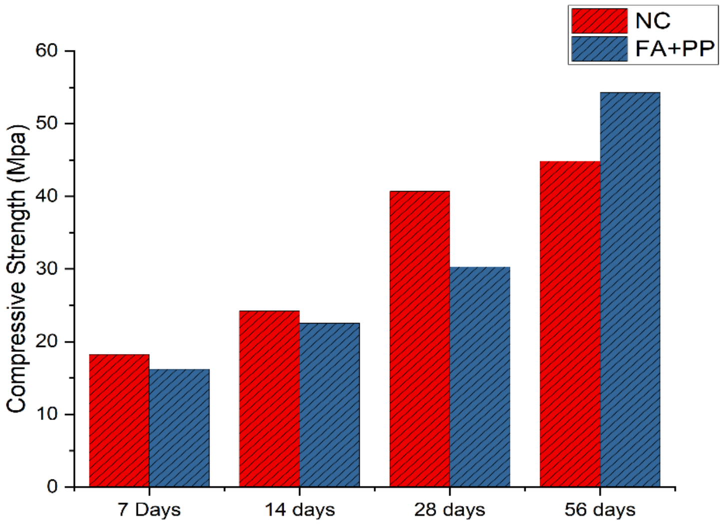


Fig. 8. Compressive strength of NC and FA+PPF concrete mixes

In Table 9, there is a comprehensive statistical analysis regarding compressive strength data of the Normal Mix (NM) and the Fly Ash with Polypropylene Fiber (FA+PP) mix at 7, 14, 28 and 56 days of curing. Average compressive strength, standard deviation, and coefficient of variation (COV) analysis is also carried out which collectively analyzes the reliability and homogeneity of the results. COVs for NM mix were low and varied from 0.99 to 2.19% among all ages, reminding us of consistent performance of this mix. The COV of FA+PP was slightly higher in the early age of up to 2.80% but this decreased dramatically to 0.38% at 56 days. This reduction in variability over time brought about by ongoing pozzolanic reactions and polypropylene fibers indicates that the FA+PP can have reliable long term structural performance.

Table 9. Statistical analysis of compressive strength for NM mixes at different curing ages for Normal Mix (NM)

Age (days)	Average (MPa)	Standard Deviation (MPa)	Coefficient of Variation (%)
7	18.22	0.18	0.99%
14	24.19	0.41	1.70%
28	40.83	0.41	1.01%
56	44.17	0.97	2.19%

Table 10. Statistical analysis of compressive strength for FA+PP mixes at different curing ages for Polypropylene + Fly Ash Mix (FA+PP)

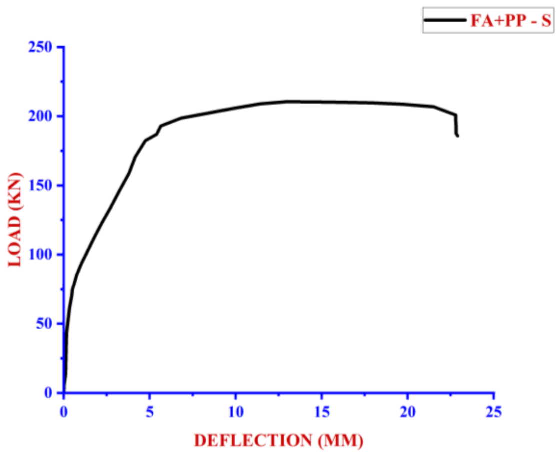
Age (days)	Average (MPa)	Standard Deviation (MPa)	Coefficient of Variation (%)
7	16.17	0.41	2.54%
14	22.83	0.64	2.80%
28	30.30	0.76	2.51%
56	54.97	0.21	0.38%

4.2. Flexural Studies of RC Beams (Load vs Deflection)

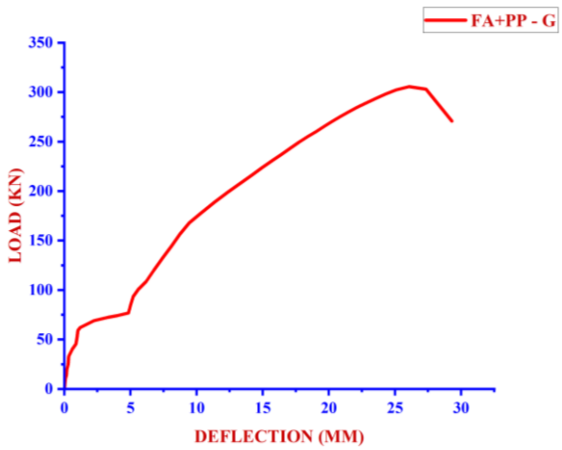
4.2.1 Load vs. Deflection Behavior of Beams

These analyses include the load vs. deflection behavior of four different configurations: FA+PP-S (Fly Ash + Polypropylene Fiber with Steel Rebars), FA+PP-G (Fly Ash + Polypropylene Fiber with GFRP Rebars), NC-S (Nominal Concrete with Steel Rebars), and NC-G (Nominal Concrete with GFRP Rebars). This work compares and presents the structural performance of these beams under flexural loading. While the FA+PP-S beam without steel reinforcement, fly ash, and polypropylene fiber only yielded a peak load of 20.5 kN at a corresponding failure deflection of 16 mm, the FA+PP-S beam with reinforcement reached the peak load of 305.6 kN at a deflection of 27.35 mm. In the first phase, the load-deflection relation was linear, displaying elastic behavior, and at high deflections, the beam remained structure intact, showing good ductility and crack resistances. On the other hand, the beam identified FA+PP-G which was reinforced GFRP rebars reached a peak load of 279.9 kN at deflection of 21.47 mm. The overall load-deflection response of FA+PP-S was a relatively less deflection compared to FA+PP-S, indicating a more brittle behavior experienced under GFRP reinforcement. While its first stiffness was lower than that of its steel-reinforced counterpart, the overall stiffness attained showed proper strength to load.

The NC-S beam, which is made of nominal concrete and reinforced with steel rebars, achieved a maximum load of 216 kN at a deflection of 15.38 mm. The main reason this beam behaved similarly to FA+PP-S but had a lower load capacity was because it lacked fly ash and polypropylene fibers, which increase strength and resistance to cracking. The steel reinforcement's adequate ductility allowed the beam to support heavier loads before failing. The NC-G beam demonstrated a maximum load of 215.7 kN at a deflection of 15.25 mm when strengthened with GFRP rebars and free of fly ash or fibers. Because GFRP rebars are more brittle and often show higher deflections before failure, this beam demonstrated less ductility than its steel-reinforced equivalent. When compared to steel reinforcement, the final deflection values indicate that GFRP reinforcement influences the failure process but does not significantly change peak load capacity.



(a)



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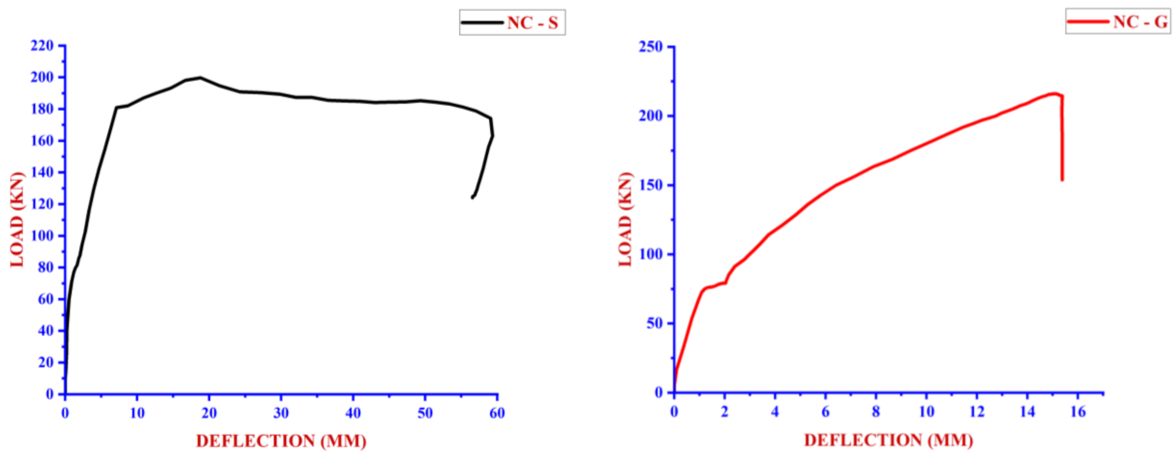


(c) (d)

Fig. 9. Load vs. Deflection Graphs (a) FA+PP – S beam (b) FA+PP - G beam (c) NC – S beam and (d) NC-G beam

When the four beam configurations were evaluated, the FA+PP-S specimen exhibited the highest ultimate load-bearing capacity, followed sequentially by FA+PP-G, NC-S, and NC-G. Despite steel-reinforced beams (FA+PP-S and NC-S) displaying greater initial stiffness, the deflection responses differed significantly, with GFRP-reinforced beams (FA+PP-G and NC-G) experiencing larger mid-span deflections due to the lower modulus of elasticity and increased flexibility of GFRP rebars. The incorporation of fly ash and polypropylene fibers in FA+PP-S and FA+PP-G enhanced overall structural efficiency, with notable improvements in both load capacity and deflection control, resulting in superior crack resistance and post-cracking behavior compared to their nominal concrete counterparts. Additionally, the results indicate FA+PP-S to be the most load bearing and ductile beam. Furthermore, FA+PP-G offers a nice alternative with comparable performance and lower corrosion risks with reinforcement provided by steel. Its performance was poorer than that of the fiber inclusion or the fly ash inclusion on nominal concrete beams, steel and GFRP rebar. Finally, it is established in this study that GFRP can replace concrete based structural steels with the cautions of brittleness nature and higher deflections.

Table 11. Ultimate load and deflection characteristics of tested beams

Mix ID	Load (KN)	Deflection (mm)
NC-G	199.7	18.8
NC-S	216.1	15.1
FA+PP-S	210.5	12.97
FA+PP-G	305.6	26.07

4.3. Comparison of Load vs. Deflection Behavior of Beams

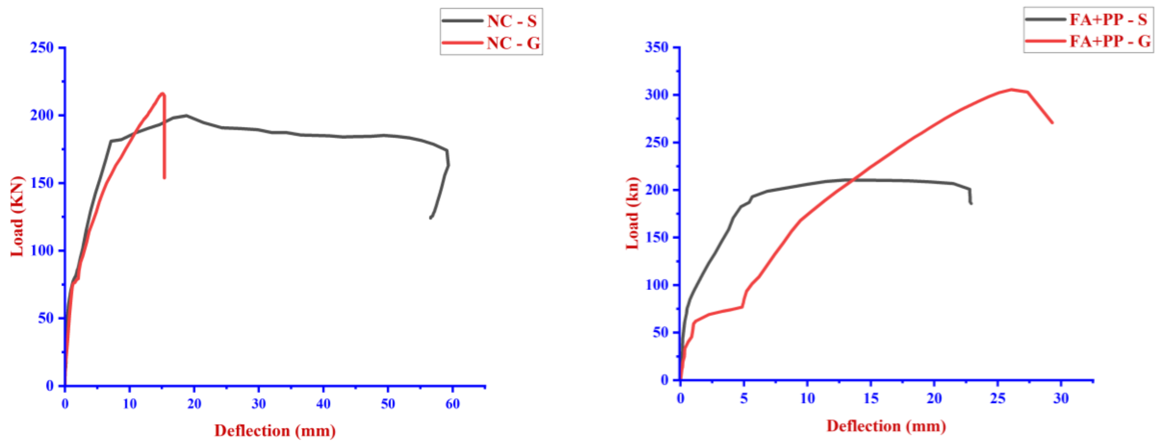
4.3.1 Comparison of NC and FA+PP Beams

The load vs. deflection behavior of the NC-S and NC-G beams was then analyzed and substantial difference were noted. Notably, NC-S beams have higher initial stiffness given the fact that steel has a higher modulus of elasticity than concrete, while NC-G beams show a more rapid increase in deflection. The peak load before failure being NC-S of 199.7 KN and NC-G of 216 KN, thus showing higher load capacity. At the maximum deflection, NC-S exhibits 57.28 mm while NC-G has 15.38 mm; this implies a better flexural stiffness. The NC-S beams exhibited plastic failure prior to failure, whereas the NC-G showed brittle failure after peak load. For ductility dependent applications GFRP's potential as viable alternative to steel reinforcement is strengthened by results showing higher load and lower deflection but must be considered for its brittleness. It is shown that GFRP rebars can serve as a sustainable, durable alternative to carbon in the fabrication of concrete structures.

Comparison was made in deflection and load behavior of FA+PP-S (fly ash + polypropylene fiber reinforced with steel reinforcement) and FA+PP-G (fly ash + polypropylene fiber reinforced with GFRP reinforcement) beams. In both cases, the deflection increased with the load, and FA+PP-S reached 29.3 mm at the maximum 270.7 KN, while FA+PP-GFRP achieved 29.3 mm at same load. Steel reinforced beams could hold more loads earlier than GFRP beams, which were also demised at the same peak (302.4 KN). FA+PP-S beams had 5.61 mm, 19.04 mm deflection at 100 KN and 200 KN respectively, and FA+PP-GFRP beams had 6.17 mm, 19.64 mm deflection at 100 KN and 200 KN respectively. Although its deflection is like the peak load, GFRP beams present advantages such as corrosion resistance, thus becoming a viable alternative for the construction in sustainable terms. The FA+PP-G beams exhibit slightly higher deflections than FA+PP-S at intermediate load levels. For instance:

- FA+PP-S deflected 5.61 mm at 100 kN, which is 0.56 mm more than FA+PP-G deflected.
- FA+PP-S and FA+PP-G were respectively 19.04 and 19.64 mm upon 200 kN.
- FA+PP-G beams deflected marginally higher but failed to crack before they displayed better stress redistribution and crack resistance, which was attributed to the fibers being polypropylene.

In addition, while both FA+PP-S and FA+PP-G delayed the propagation of crack and had greater energy absorption compared to the NC mixes, a brittle failure of FA+PP-G remained. Nevertheless, the introduction of fibers helped enhancing post peak behavior and cracked bridging, as well as load redistribution, alleviating for intrinsic brittleness of GFRP reinforced systems.



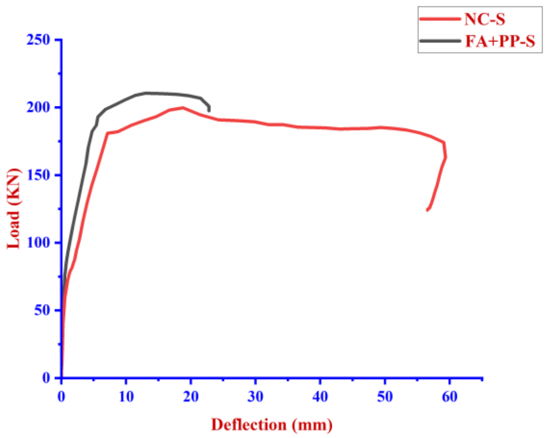
(a) (b)

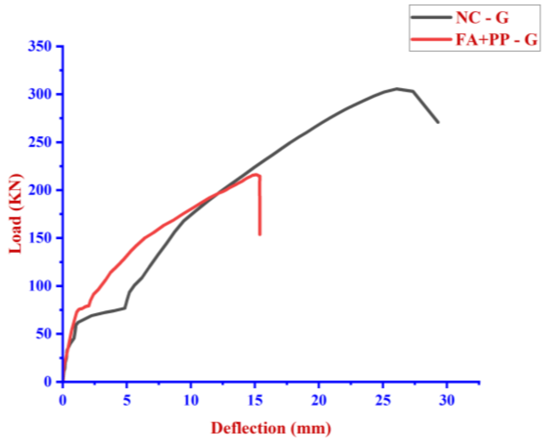
Fig. 10. Comparison of load vs. deflection graph for (a) NC and (b)FA+PP Beams

4.3.2 Comparison of Steel and GFRP Beams

FA+PP-S (Fly Ash + Polypropylene Fiber and Steel Reinforced) NC-S (Nominal Concrete and Steel Reinforced) beams were analyzed for the load vs. deflection behavior. At applied load, both the beam types experienced an initial increase in deflection, until FA+PP-S beam deflected less sharply than the NC-S beams. Maximum load experienced by the FA+PP-S was 210.5 kN with a maximum displacement of 22.79 mm and by the NC-S was 210.3 kN with a maximum displacement of 57.28 mm at failure. The flexural stiffness of the NC-S beams in NC-S beams was lower as deflection increased more rapidly at higher loads and yielded at a higher value of deflection. Both beam types had stable loading post peak but NC-S deflected and experienced more plastic deformation before failure. It is concluded that both beam types have the same load carrying capacity, but FA+PP-S beams have better deflection control leading to better flexural performance and better overall structural behavior.

The FA+PP-G (Fly Ash + Polypropylene Fiber + GFRP reinforcement) and NC-G (Nominal concrete + GFRP reinforcement) beams were analyzed on basis of load versus deflection behavior. There was a less abrupt increase in deflection of FA+PP-G beams under applied load as compared to NC-G beams. The highest load occurring at the peak was 302.4 kN for FA+PP-G, while NC-G beamed out at 216 kN and 15.38 mm at deflection. Deflection gradually increased on increasing load for FA+PP-G beams, which exhibits more flexible response prior to failure, and deflection becomes constant after the maximum load for NC-G beams. The deflection capacity of FA+PP-G beams was found to be greater than that of NC-G beams and its load carrying capacity is also higher. Therefore, FA+PP-G beams shows better ductility than NC-G beams. Therefore, these results suggest the application of FA+PP-G beams as an alternative to GFRP beams in concrete structures in terms of load capacity and flexural performance. Nevertheless, their higher deflections should be considered in design.



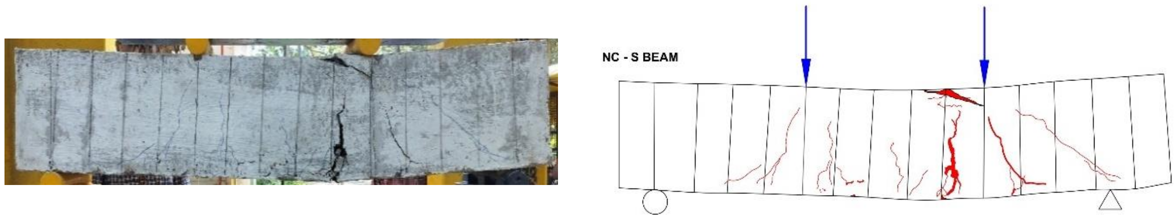


(a) (b)

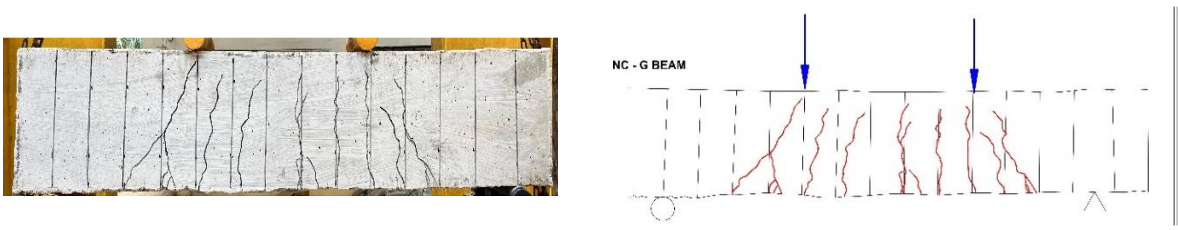
Fig. 11. Comparison of load vs. deflection graph for (a) steel and (b) GFRP beams

4.4. Crack Behavior

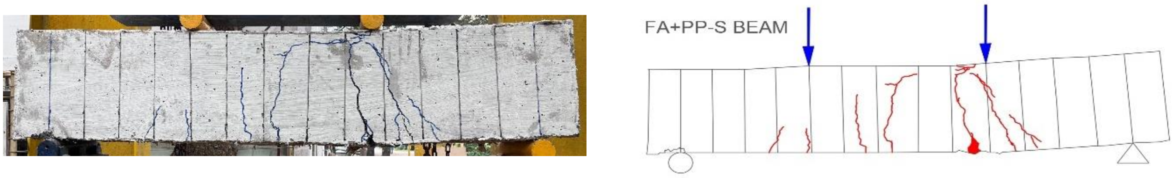
Reinforced concrete beams remain structurally and serviceably strong only if the crack formation and propagation in them can be inhibited. Four beam types were evaluated in the study, the FA+PP-S (fly ash + polypropylene fiber + steel rebars), FA+PP-G (fly ash + polypropylene fiber + GFRP rebars), NC-S (nominal concrete + steel rebars) and NC-G (nominal concrete + GFRP rebars). Visible cracks appeared at lower load levels in NC-S and NC-G beams than by FA+PP-S and FA+PP-G beams.' The delay of the onset of cracks by polypropylene fibers present in the FA+PP beams was due to the fibers' success in distribution of stress. Steel rebars reinforced beams (NC-S and FA+PP-S) especially had better crack control from the ductility of the steel that provides energy dissipation before failure. Both toughness and crack widening resistance were improved in the FA+PP-S beam. Reinforced with GFRP rebars, the NC-G and FA+PP-G beams showed wider cracks than their counterparts with steel rebars. GFRPs lower modulus of elasticity explains it: it allows greater deformations before failure.



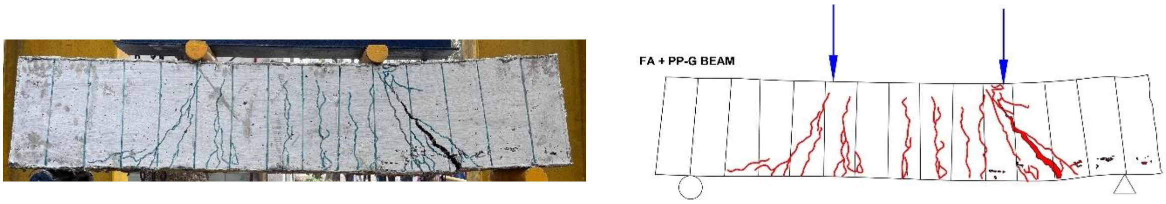
(a)



(b)



(c)



(d)

Fig. 12. Crack pattern of RC beams (a) NC- S Beam (b) NC – G Beam (c) FA+PP – S Beam (d) FA+PP – G Beam

Nevertheless, fly ash+ polypropylene fibers (FA+PP G) beams had better crack control because of the synergistic effect of polypropylene fibers and fly ash. The ductile failure modes of the NC-S and FA+PP-S beams experience gradual crack widening and plastic deformations before ultimate failure. On the other hand, NC-G and FA+PP-G beams had more brittle failure characteristics with sudden crack propagation to induce failure. However, in FA+PP-G beams, the presence of fibers bridging offered an effect that enhanced post crack load resistance. As a result, the crack resistance and durability of the steel as well as GFRP reinforced FA+PP mixes with fly ash and polypropylene fibers was enhanced over the control FA+PP mixer to improve its suitability for structural applications where high crack control is required.

5. Conclusions

The effect of fiber and fly ash using this experimental study was to evaluate the mechanical performance as well as durability of reinforced concrete. Compressive strength, flexural response, crack behavior, and corrosion resistance of the concrete were examined on incorporating 20 percent fly ash as cement replacement and 1 percent polypropylene fibers by volume in a study. According to the experimental findings, these can be inferred.

- The addition of 1% polypropylene fibers and 20% fly ash increases the long term compressive strength, FA+PP mixes attained 54.98 MPa at 56 days but exceeded the nominal mix as the pozzolanic reaction and matrix densification are delayed. High load bearing capacity (305.6 kN) was observed in FA+PP-S beams and FA+PP-G beams performed well in complying with the strength (279.9 kN), thereby proving the synergy between fibers and fly ash in reinforced concrete systems.
- Steel reinforced beams were ductile and GFRP reinforced beams were brittle. The failure mode for FA+PP-G beams is improved with incorporation of polypropylene fibers as they delay the crack propagation and improve the post crack stability. They also showed improvement in both energy dissipation capacity and deformation capacity by virtue of fiber inclusion in GFRP reinforced beams, especially FA+PP-G.
- Crack propagation was well controlled by the polypropylene fibers. This suggests that FA+PP-G beams had reduced crack width and FA+PP-S beams had fine, closely spaced cracks, both of which represent improved crack resistance from fiber bridging. Fly ash use saves cement demand, lower CO_2 emissions and fosters sustainable construction. FA + PP-G systems are corrosion free with the help of GFRP rebars that provide risk free solutions for harsh corrosive environments like coastal and marine structures.
- Coring, combining fly ash and polypropylene fibers with the GFRP reinforcement thus produces a corrosion resistant, mechanically efficient, durable composite system and

justifies a role as a candidate for infrastructure systems that may be required for long term resilience in aggressive exposure.

- Further research works can study the effect of different fiber types (e.g., basalt, carbon, steel, or hybrid fibers) on performance of the mechanical and durability of fly ash concrete and determine quite design optimum fiber reinforcement strategies for various applications. Examine how the total fiber content changes past 1% to establish the amount of fiber which optimizes workability, strength, and crack resistance in fiber reinforced fly ash concrete. Study the interaction between fly ash and other supplementary cementitious materials, silica fume, metakaolin, or slag to improve early age and long-term performance.

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