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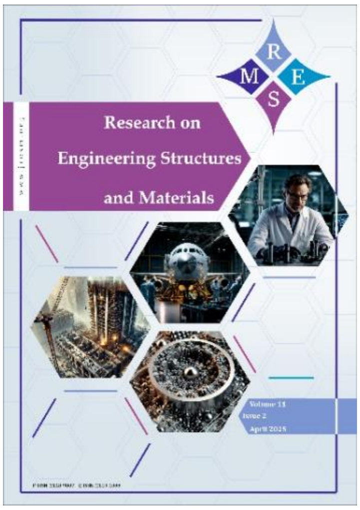

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Research Article

Experimental investigation of functionally graded basalt-glass hybrid fiber reinforced beams

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Abstract

This study presents an in-depth experimental and analytical examination of the flexural behavior of full-scale functionally graded high-performance concrete (FGHPC) beams reinforced with a hybrid combination of basalt and glass fibers. The control mix utilized was M70 grade high-performance concrete (HPC), while the functional gradation was attained through the incorporation of hybrid fibers (basalt and glass) of two distinct lengths (6 mm and 12 mm) in various proportions distributed throughout the tensile zone of the beam. The beams were cast in layered configurations to evaluate the influence of fiber gradation on flexural strength, stiffness, ductility, and crack propagation control. Four-point bending tests were performed on simply supported beams measuring 230 × 300 × 2000 mm to determine the ultimate load capacity, mid-span deflection, and stress–strain response. Additionally, a finite element (FE) model was developed in ABAQUS employing the Simplified Concrete Damage Plasticity (SCDP) approach to replicate the flexural performance of M70 grade concrete beams. The model incorporated concrete, steel reinforcement, and hybrid fibers using embedded constraints, and was validated against experimental results, showing strong correlation. The optimum graded hybrid configuration (0.3% basalt + 0.2% glass fibers) exhibited an 18% increase in ultimate load capacity and approximately 50% higher mid-span deflection compared to the control HPC beam, demonstrating significant enhancement in flexural strength and ductility. The findings revealed that functionally graded basalt–glass hybrid fiber reinforced concrete (FG-HFRC) beams exhibited higher load-carrying capacity, stiffness, mid-span deflection, and post-cracking ductility than the control HPC beam. Basalt fibers enhanced crack resistance, while glass fibers improved energy absorption and deformation capacity. Thus, functional gradation of hybrid fibers in HPC beams offers a material-efficient fiber utilization strategy to achieve superior flexural performance and durability.

1. Introduction

Concrete is the most extensively utilized construction material globally, valued for its exceptional compressive strength, long-term durability, and adaptability to diverse structural applications. However, it exhibits a quasi-brittle nature, characterized by limited tensile strength and poor post-cracking ductility [1]. To overcome these shortcomings, several advanced concrete composites have been developed, including fiber-reinforced concrete (FRC), high-strength concrete (HSC), and high-performance concrete (HPC). Among these, FRC has received significant attention for its ability to enhance tensile behavior, fracture resistance, and toughness through the random dispersion of discrete fibers within the matrix. The performance of FRC depends mainly on the fiber type, aspect ratio, volume fraction, and its distribution [2,3]. Each type of fiber enhances a specific mechanical characteristic of concrete.

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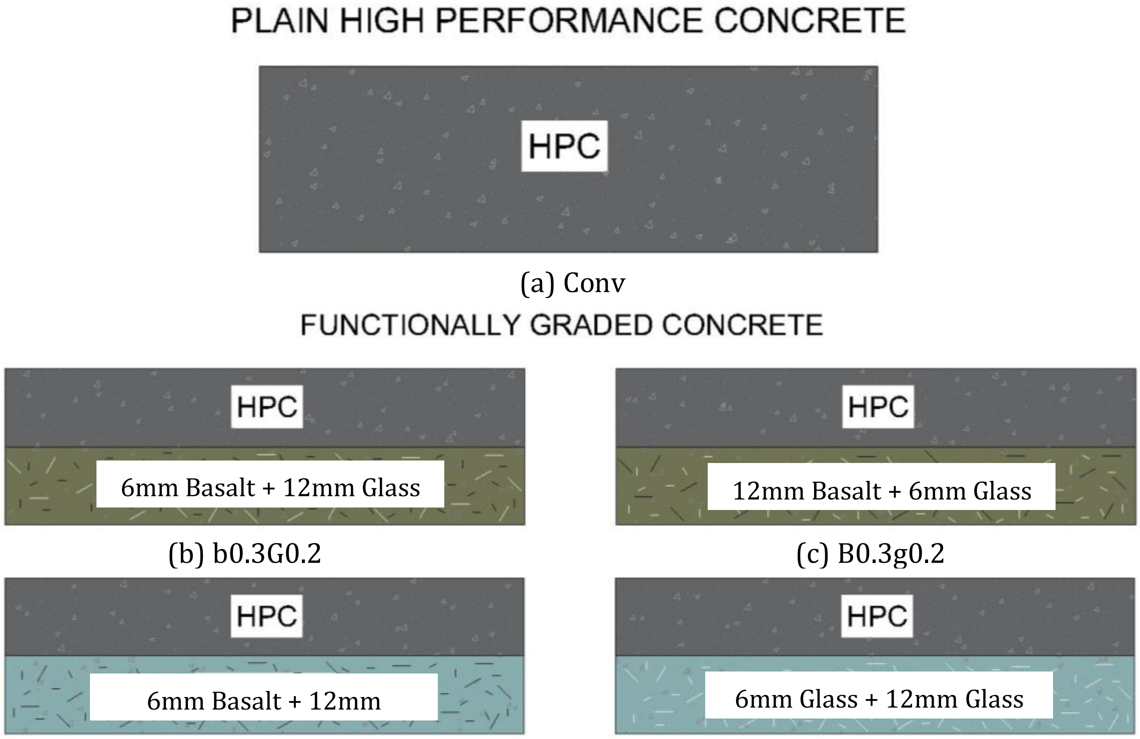
The incorporation of two or more fiber types in a single matrix, known as hybrid fiber reinforced concrete (HFRC), enables the synergistic use of their complementary properties, resulting in superior mechanical and durability performance compared to mono fiber reinforced concrete (MFRC) [4,5]. Short fibers are especially effective in restraining the initiation of microcracks and enhancing peak strength, whereas longer fibers act as bridges across macrocracks, thereby improving ductility and toughness during the post-peak phase [6]. The strategic combination of short and long fibers in varying proportions leads to graded fiber-reinforced concrete (GFRC), which exhibits enhanced strength, strain capacity, and energy absorption compared to single-length FRC [7,8]. While FRC improves overall performance, the uniform dispersion of fibers throughout the concrete volume may not always be cost-effective or necessary, especially for structural members predominantly subjected to flexure. In such cases, it is more efficient to introduce fibers selectively in tension zones. This concept is realized through functionally graded concrete (FGC), where the composition or properties of the material vary spatially within a structural element to meet performance requirements specific to different zones [9-12].

FGC can be produced either through a layered approach or by continuous gradation of materials, providing improved durability, fracture resistance, and load-bearing capacity [13]. Extensive research has been conducted on the flexural performance of FGC beams with various fiber volume distributions, and it has been reported that a gradual reduction of fiber content from the tension to the compression zone optimizes both strength and cost efficiency. Rathi et al. examined the layered process for casting functionally graded concrete components. Investigations on the structural viability of FGC have shown favorable results and highlighted the possibility for gradation in structural engineering. The functionally graded concrete (FGC) elements demonstrated improved durability, fracture resistance, and load-carrying capacity [14]. In an experimental study, Othman, M. A. et al. explored the flexural response of FGC beams by testing fourteen different beam configurations, including full-depth fiber-reinforced concrete (FRC) and FGC with varied fiber volume distributions. Results indicated that the flexural strength of all functionally graded FRC specimens ranged between 94% and 100% of that of the full-depth FRC beams. Optimal cost efficiency was achieved by gradually reducing the fiber volume fraction toward the tension zone of the beam. The tension–compression FRC specimen with a 1.5% fiber volume fraction exhibited a toughness index of 93% relative to full-depth FRC, while the tension-only FRC specimen with a 0.5% fiber volume fraction showed a toughness index of 49% [15]. Studies performed on two- and three-layered FGC beams observed significant improvements in load-carrying capacity, stiffness, and ductility compared to conventional reinforced concrete beams. Pratama et al. investigated the load-bearing capacity, deflection, stiffness, and ductility of FGC beams utilizing M25 and M30 concrete grades in full depth, as well as in two- and three-layered configurations. The findings indicated that the FGC beam with three layers of concrete had an ultimate load increase of 0.83%, a deflection reduction of 29.5%, a stiffness enhancement of 12.03%, and a ductility improvement of 20.06% in comparison to full depth M25 grade concrete RCC beam [16]. Recent investigations on FGC reinforced with hooked-end steel fibers have demonstrated the effectiveness of spatial gradation of fiber dosage in achieving enhanced flexural and fracture performance with reduced material usage. The study involving forty-eight beam specimens showed that the FGFRC beam with an effective fiber content of 0.9% exhibited comparable flexural strength to the optimal 1.2% FRC beam, highlighting the potential of graded configurations for cost-effective structural performance improvement [17].

Recent research on functionally graded concrete flexural members (FGCFMs) reinforced with hybrid steel and fiber-reinforced polymer (FRP) bars has demonstrated remarkable improvements in seismic performance. The graded distribution of flexural strength enabled the development of multiple plastic regions, resulting in increases of up to 147% in deformability and over 50% in ductility compared to conventional reinforced concrete members [18]. Numerical studies by various researchers have validated that FGC models can accurately predict shear and flexural behavior when supported by experimental evidence. Milad Hafezolghorani et al. established a simplified concrete damage plasticity (SCDP) model incorporating a damage parameter, strain hardening, softening regulations, and additional elements for M20 to M50 grade concretes. The outcomes of the simply supported prestressed beam models, utilizing various concrete grades and created in the finite element-based Abaqus program, exhibited strong correlation with previous empirical formulas. The prestressed concrete beam's mid-span displacement, tension, and compressive stress were all accurately predicted by the developed FE model [19]. Using homogeneous theory, Yue Li et al. created a theoretical model to forecast the fiber-reinforced concrete's elastic modulus and Poison's ratio [20]. Despite these advancements, research integrating the combination of basalt and glass fibers into FGC remains limited. Basalt fibers offer excellent tensile strength, chemical stability, and high-temperature resistance, while glass fibers contribute to improved deformability and surface bonding. The combined use of these fibers in a graded system is expected to provide a balanced enhancement in both strength and ductility. Moreover, the integration of experimental and finite element (FE) analysis for such hybrid functionally graded systems has not been extensively reported. In the present study, the term functionally graded concrete refers to a step-wise spatial variation of fiber reinforcement along the beam depth, achieved through layered casting. Although not continuously graded in a mathematical sense, this approach enables intentional tailoring of mechanical properties in accordance with flexural stress demand and is widely adopted in practical FGC applications due to constructability considerations. Hence, the present study focuses on the experimental and analytical evaluation of full-scale M70 grade high-performance concrete beams incorporating functionally graded hybrid basalt–glass fibers. The experimental program includes four-point flexural testing to determine load-deflection response, stress-strain behavior, and ultimate load capacity. Complementary finite element modeling using ABAQUS software, based on the Simplified Concrete Damage Plasticity (SCDP) model, is conducted to simulate and validate experimental observations. The study aims to establish the structural effectiveness of functional gradation of hybrid fibers in enhancing strength, stiffness, ductility, and crack control in high-performance concrete beams.

2. Experimental Program

The present study investigates the flexural performance of full-scale M70 high-performance concrete (HPC) beams incorporating functionally graded hybrid fibers consisting of basalt and glass. Three types of beams were examined: HPC, functionally graded hybrid fiber reinforced high performance concrete (HyFRHPC), and graded fiber reinforced high performance concrete (GrFRHPC).



(a) Conv

(b) b0.3G0.2

(c) B0.3g0.2

(d) b0.3B0.2

(e) g0.3G0.2

Fig. 1. The plain HPC and Functionally Graded Concrete mixes adopted for the current study

In the present study, HyFRHPC refers to functionally graded high-performance concrete beams incorporating a hybrid combination of basalt and glass fibers within the tensile zone, without variation in fiber length distribution across the layer. The mix designations b0.3G0.2 and B0.3g0.2 fall under the HyFRHPC category, where hybridization is achieved by combining basalt and glass fibers of fixed lengths within the tensile region. GrFRHPC denotes functionally graded high-performance concrete beams in which gradation is achieved through a controlled distribution of fibers of different lengths within the tensile zone. The mixes b0.3B0.2 and g0.3G0.2 represent GrFRHPC configurations, where fiber gradation is introduced by varying the proportion of short and long fibers of the same fiber type. The control beam without fiber is designated as Conv. The objective is to evaluate the influence of fiber gradation and hybridization on load-carrying capacity, stiffness, and ductility under four-point bending. The mix design was based on M70 grade concrete, and fiber proportions were varied according to the desired gradation pattern. The experimental matrix and grouping of mixes are illustrated in Figure 1.

2.1 Materials

KCP OPC 53 grade cement according to IS 269-2015 [21], JSW GGBS conforming to IS 12089-1987 [22], and Ecomac Micro Silica complying to IS 15388-2003 [23] were utilized. Zone II Krishna river sand compliant with IS 383-2016 [24], along with coarse aggregates of 12.5mm and 6mm sizes in proportions of 60% and 40%, respectively, conforming to IS 383-2016, were used. The gradation of coarse and fine aggregates used are presented in Fig. 2. Potable water complying to IS 456-2000 [25] and Mac Hyperplast PC 310, a PC-based superplasticizer complying to IS 9103-1999 [26], were used. Alkali-resistant glass fibers from Owens Corning, measuring 6mm and 12mm, were utilized. Basalt fibers measuring 6mm and 12mm were utilized. The physical and mechanical properties of the fibers are summarized in Table 3.

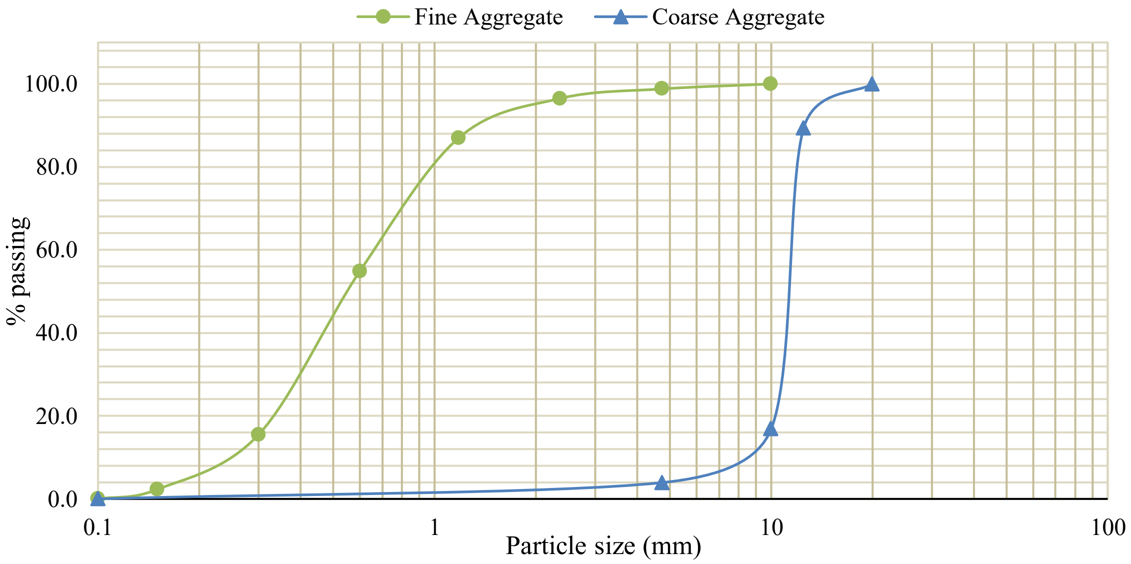


Fig. 2. Particle size distribution of aggregates

Table 3. Fiber properties

Property	Basalt Fiber		Glass Fiber	
Length (mm)	6	12	6	12
Diameter (mm)	0.015	0.015	0.014	0.014
Aspect Ratio	400	800	428.57	857.14
Tensile Strength (MPa)	3500	3500	1400	1400
Elastic Modulus (GPa)	93	93	72	72

2.2 Mix Proportions

The concrete mix design for M70 grade HPC was developed following IS 10262:2019 and IS 456:2000 guidelines. Several trial mixes were tested to satisfy strength, workability, and durability criteria. The finalized mix proportions are given in Table 4. Functionally graded mixes incorporated varying fiber combinations across the depth. The lower tensile zone contained fiber-reinforced concrete (FRC), while the upper compression zone consisted of plain HPC. The details of fiber dosage and configuration for each mix type are provided in Table 5. The total fiber volume fraction was fixed at 0.5% based on preliminary trials and published literature, balancing workability, fiber dispersion, and mechanical performance for high-performance concrete. Higher fiber contents were avoided to prevent segregation and balling, particularly in layered casting.

Table 4. Mix proportion

Mix Designation	Cement (kg/m^3)	GGBS (kg/m^3)	Silica Fume (kg/m^3)	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Super Plasticizer (kg/m^3)
M70	343	200	29	156	1055	697	2.57

Table 5. Mixtures and Volume of fibers

Mix Designation	Basalt fiber 6mm	Basalt Fiber 12mm	Glass Fiber 6mm	Glass Fiber 12mm
Conv	-	-	-	-
b0.3B0.2	60%	40%	-	-
g0.3G0.2	-	-	60%	40%
b0.3G0.2	60%	-	-	40%
B0.3g0.2	-	60%	40%	-

2.3 Casting

For functionally graded beams, the lower fiber-reinforced layer was cast first and compacted using a needle vibrator. The upper plain HPC layer was placed immediately after the initial layer reached a plastic state to ensure adequate interlayer bonding. No visible delamination or interface cracking was observed after testing, confirming monolithic behavior. Beam molds of 230 × 300 × 2000 mm were fabricated and prepared for casting. Before casting, the inner faces of the beam molds were lubricated with petroleum-based mold release oil. The reinforcement, as per the design, was tied and inserted into the beam molds. Cover blocks were fabricated beforehand and positioned beneath the reinforcement. The constituent materials were properly weighed according to the mix proportion. The coarse aggregate and fine aggregate were added into the mixer and mixed thoroughly for 2 minutes. Cement, silica fume and GGBS were added to the mixture and blended thoroughly for 2 minutes. Water, together with the superplasticizer was incorporated into the mixture and permitted to blend for 1.5–2 minutes. For fiber-reinforced mixes, fibers were gradually dispersed during the final mixing phase to ensure uniform distribution and avoid balling. The concrete was subsequently collected from the pan mixer into mortar pans and placed into the beam molds. The beam mold for the control specimen was filled with high-performance concrete and meticulously compacted using a needle vibrator. For functionally graded specimens, fiber-reinforced concrete was placed in the lower tensile zone of the beam, while plain high-performance concrete was placed in the compression zone. The lower layer was compacted and the upper layer was cast immediately thereafter to ensure adequate interlayer bonding and monolithic action. The beams were permitted to set for 24 hours. After demolding at 24 hours, all beam specimens were moist-cured for 28 days by covering with continuously wetted jute sacks under laboratory conditions at a temperature of 27 ± 2°C, followed by air drying prior to testing. The surface was subsequently smoothed with emery paper and coated with whitewash. Grids measuring 50mm were inscribed on the surfaces of both faces. All beams were reinforced with identical longitudinal reinforcement and shear reinforcement as per the design shown in Fig. 3 to ensure flexure-dominant behavior and allow direct comparison between specimens.

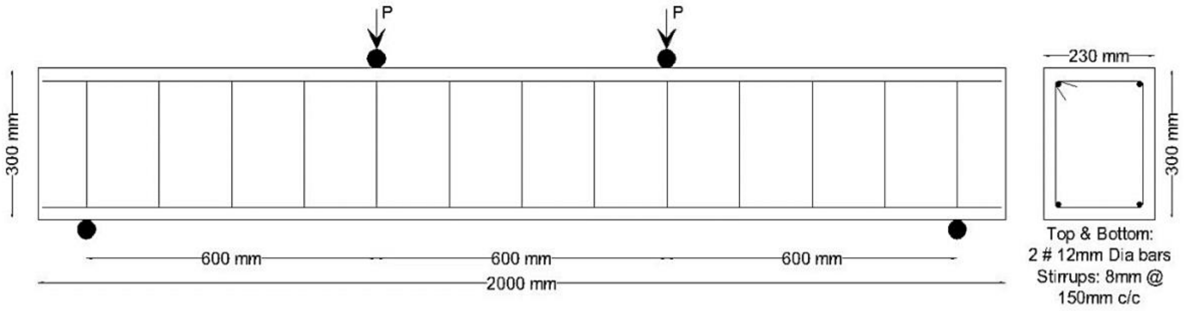


Fig. 3. Reinforcement details of the beam

2.4 Testing

Due to the large-scale nature of beam specimens, one representative beam per configuration was tested, which is consistent with prior experimental studies on full-scale structural members. The beam specimens were tested under four-point bending using a stress-controlled hydraulic loading frame. The effective span was maintained at 1800 mm, and loads were applied at one-third and two-thirds of the span, as shown in Fig. 3. The LVDT was positioned at the center of the beam's bottom face to measure vertical displacement. The load cell was descended, and load was exerted on the spreading steel I-section and subsequently on the loading heads. The load, displacement, stress, strain, and ultimate failure load were documented using the data acquisition system. The stress-strain curves were generated for each tested beam specimen. The stress-strain behavior of the functionally graded beams was compared with that of the control specimen. The results were subsequently contrasted with those obtained from analytical models developed using Abaqus software.

3. Modelling

The finite element (FE) modeling of functionally graded hybrid fiber-reinforced concrete (FGHFRC) beams was performed using ABAQUS to simulate the flexural behavior observed in experiments. The beam dimensions were 230 × 300 × 2000 mm, identical to the experimental specimens. The assembly of the components in Abaqus software is shown in Fig. 4.

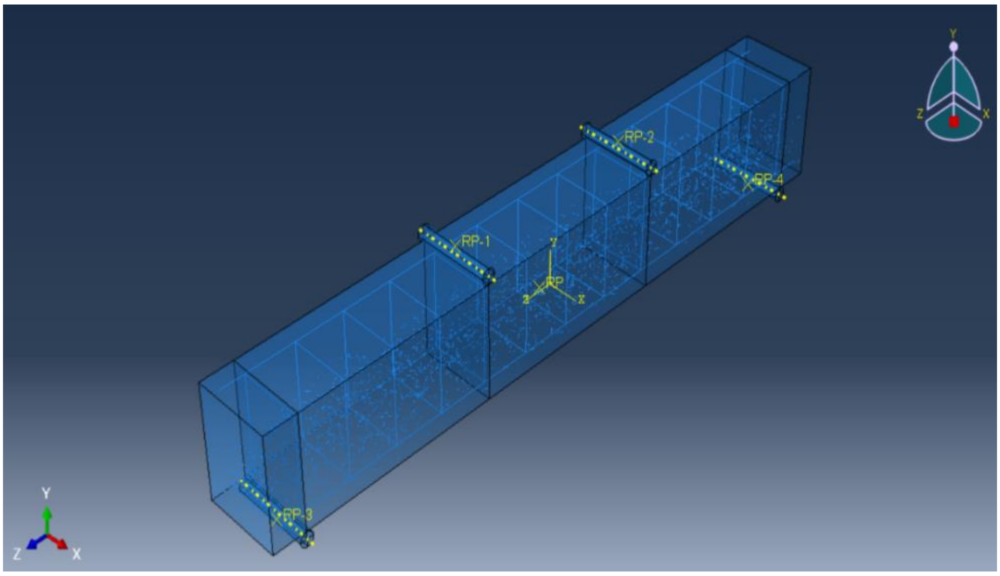


Fig. 4. Assembly of various elements in abaqus model

The model was developed using a modular approach, with individual components i.e. concrete, reinforcement, and hybrid fibers created separately and assembled into a composite system. Concrete was modeled using 8-node linear brick elements (C3D8R), suitable for nonlinear static analysis. The steel reinforcement (main bars and stirrups) and fibers were modeled using 2-node 3D truss elements (T3D2), assuming perfect bond through the embedded region constraint. This assumption neglects fiber–matrix debonding and pull-out behavior and may slightly overestimate post-cracking stiffness and load-carrying capacity. Nevertheless, the assumption is commonly adopted for global structural response prediction. Future models may incorporate bond–slip interface laws to simulate fiber pull-out more realistically. Fibers were generated via Python programming, and the file was subsequently imported into Abaqus software. Concrete behavior was represented using the Simplified Concrete Damage Plasticity (SCDP) model, which accurately captures both compressive and tensile nonlinearities. The compressive stress–strain curve was derived from the Kent and Park model [19], while tensile softening behavior followed the modified tension softening model proposed by Allam et al [27]. The material parameters for modelling were adopted as per Table 6. The elastic modulus (E = 41.8 GPa) and Poisson's ratio (0.20) correspond to M70 HPC, derived from experimental tests. Steel reinforcement was modeled as an elastic–plastic material with E = 200 GPa and yield strength = 500 MPa.

Table 6: Concrete material properties as per SCDP model

Material properties		Plasticity parameters	
Concrete grade	M70	Dilation Angle	40
Concrete Elasticity		Eccentricity	0.1
Elastic Modulus (GPa)	41.8	fb0/fc0	1.16
Poisson's ratio	0.20	K	0.667
		Viscosity parameter	0
Concrete compressive behavior		Concrete compression damage	
Yield stress (MPa)	Inelastic strain	Damage parameter	Inelastic strain
35	0.00000	0	0.00000
42	0.00015	0	0.00015
49	0.00032	0	0.00032
56	0.00052	0	0.00052
63	0.00078	0	0.00078
70	0.00141	0	0.00141
63	0.00205	0.10	0.00205
56	0.00231	0.20	0.00231
49	0.00251	0.30	0.00251
42	0.00268	0.40	0.00268
35	0.00283	0.50	0.00283
28	0.00296	0.60	0.00296
21	0.00309	0.70	0.00309
14	0.00320	0.80	0.00320
Concrete tensile behavior		Concrete tension damage	
Yield stress (MPa)	Cracking strain	Damage parameter	Cracking strain
5.85	0	0	0
3.9	0.00020	0.333	0.00020
2.2	0.00048	0.625	0.00048
0.98	0.00093	0.833	0.00093

The hybrid fibers were modeled as discrete, randomly oriented truss elements confined to the tensile zone (bottom half of the beam), representing realistic gradation. Although fibers were assumed to be randomly distributed, complete randomness is difficult to achieve in large-scale specimens due to conventional mixing and casting processes, which may cause preferential alignment near formwork and along the casting direction. In this study, fibers were carefully dispersed to minimize clustering; however, some orientation bias cannot be excluded. In the FE model, fibers were idealized as randomly distributed truss elements in the tensile zone, assuming isotropic orientation, which may slightly overestimate post-cracking stiffness. This limitation is acknowledged, and future studies incorporating orientation-sensitive modeling approaches are recommended. The beam was modeled as simply supported, with one end acting as a pinned support ($U_x = U_y = U_z = 0$) and the other as a roller support ($U_y = U_z = 0$). Load was applied as two concentrated loads at one-third and two-thirds of the span to simulate four-point bending. Interaction between concrete and steel plates was defined using a surface-to-surface contact with a friction coefficient of 0.3. The model output included load–deflection curves, stress and strain distributions. Numerical predictions were validated against experimental results in terms of ultimate load capacity and mid-span deflection.

4. Results and Discussion

Figure 5 shows the experimental load–deflection curves for the control and functionally graded hybrid fiber reinforced high-performance concrete (FGHFRC) beams under four-point bending. The control M70 HPC beam (Conv) exhibited a linear load–deflection response up to first cracking, followed by a rapid stiffness degradation and brittle failure. In contrast, all fiber-reinforced and functionally graded beams demonstrated enhanced load-carrying capacity, improved post-cracking stiffness, and extended ductile behavior before failure. The load-displacement curves revealed that the incorporation of fibers enhanced both the ultimate load and the mid-span displacement of the beams. The hybrid and graded fiber mixes sustained loads beyond the first-crack stage, indicating enhanced post-cracking ductility and energy absorption. The graded fiber configuration was particularly effective in distributing load across the tensile zone, leading to a smoother transition from elastic to plastic stages. Based on observed crack patterns and established fiber behavior reported in literature, basalt fibers are inferred to contribute to early microcrack restraint, while glass fibers enhance post-cracking deformation capacity by bridging wider cracks. Among the tested specimens, the b0.3G0.2 beam (containing 0.3% basalt and 0.2% glass fibers) recorded the highest ultimate load of 225 kN, corresponding to a mid-span deflection of 21 mm, which is 18% higher load and 50% greater deflection than the control beam. The b0.3B0.2 and B0.3g0.2 mixes also exhibited superior flexural strength (221–222 kN) compared to the plain HPC. These results confirm that the synergistic action of basalt and glass fibers effectively bridged both micro- and macro-cracks, delaying crack coalescence and enhancing the energy absorption capacity.

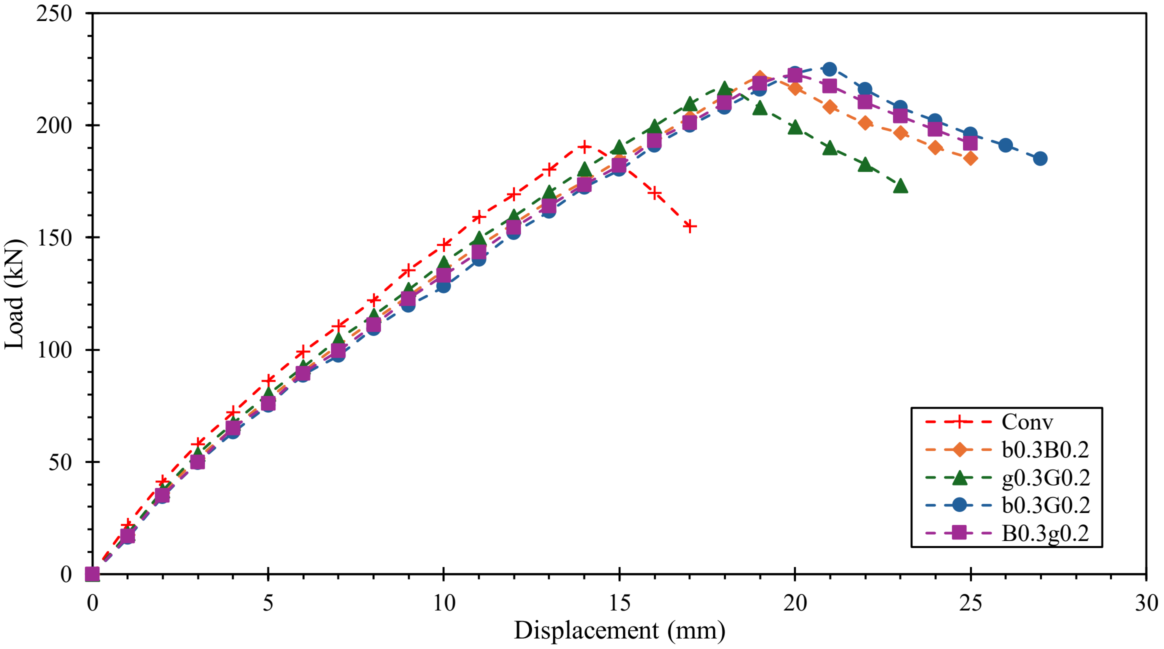


Fig.5. Experimental Load vs Displacement curves

Visual examination of the beam surfaces of fiber-reinforced specimens showed distinct crack patterns. When compared with control HPC beam, hybrid and graded fiber beams exhibited multiple fine cracks with narrower widths distributed along the pure bending region, indicating effective crack bridging and improved energy dissipation. Failure in all fiber-reinforced specimens occurred through progressive flexural cracking followed by localized crushing near the loading points, confirming a flexure-dominant mode. The absence of premature shear failure in the graded beams confirmed the adequate contribution of the fibers and uniform stress transfer across layers.

Fig. 6. Tested Beam Specimen

The finite element model successfully reproduced the global behavior observed in experiments. The predicted cracking patterns, stress contours, and load–deflection responses aligned closely with the experimental observations. The FE model captured both the initial stiffness region and the nonlinear post-cracking response, validating the use of the SCDP model for high-performance concrete with fiber gradation. The load–deflection trend obtained from the FE analysis (Fig. 7) closely mirrored the experimental curves, validating the efficiency of the SCDP model in predicting flexural response.

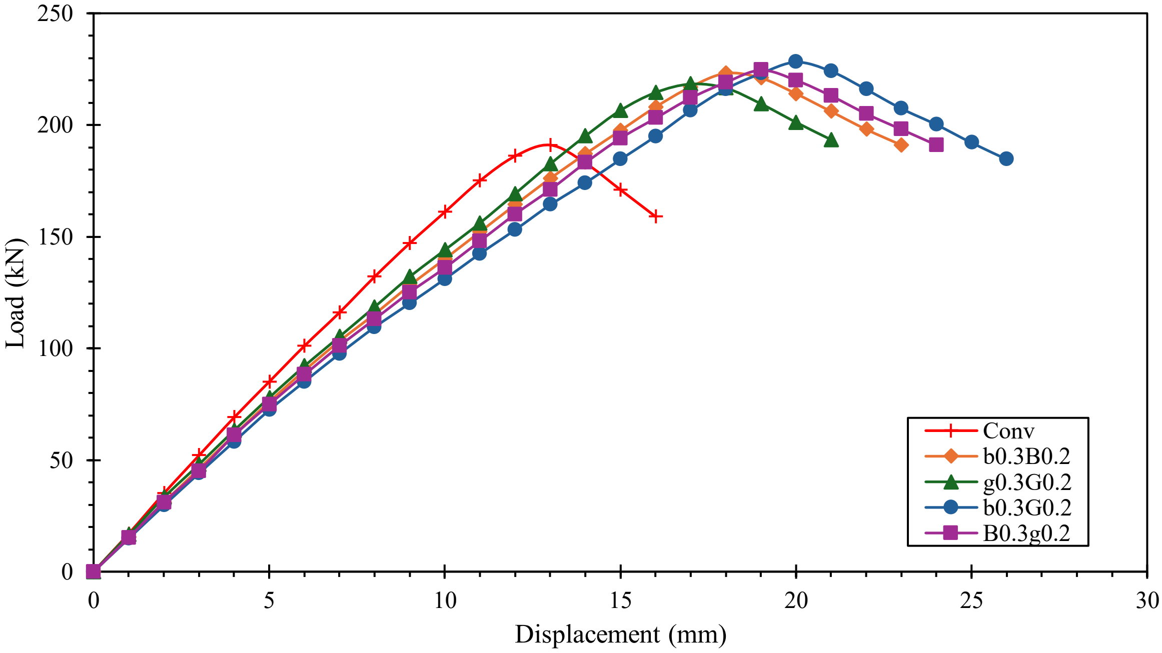


Fig. 7. Analytical Load vs Displacement Curves

The deviation between analytical and experimental ultimate loads was within 2–3%, and the difference in mid-span deflection was less than 5% (Table 8), confirming the robustness of the FE model. The minor discrepancies between experimental and analytical results can be attributed to simplifications such as the assumption of a perfect bond in the embedded region constraint and the absence of random fiber orientation effects in the model. Nevertheless, the correlation of results demonstrates that the developed FE framework can effectively simulate the structural response of functionally graded hybrid fiber-reinforced beams.

Table 8. Ultimate load and displacement

Mix Designation	Ultimate Load (kN)		Mid-Span Displacement (mm)	
	Experimental	Analytical	Experimental	Analytical
Conv	190.5	191	14	13
b0.3B0.2	221.2	223.1	19	18
g0.3G0.2	216.5	218.3	18	17
b0.3G0.2	225.0	228.1	21	20
B0.3g0.2	222.2	224.5	20	19

5. Conclusions

This study conducted both experimental and numerical investigations on the flexural behavior of full-scale M70 grade high-performance concrete (HPC) beams reinforced with functionally graded basalt–glass hybrid fibers. The research aimed to evaluate the effectiveness of fiber gradation and hybridization in enhancing the structural performance of HPC beams. Based on comprehensive laboratory testing and validated finite element (FE) simulations, the following key findings were established:

- Functional gradation and hybridization of basalt and glass fibers considerably improved overall flexural performance compared to the control HPC beam. The inclusion of fibers exclusively in the tensile zone proved to be both structurally efficient and economically viable, minimizing material usage without compromising strength.
- The b0.3G0.2 mix configuration (0.3% basalt + 0.2% glass fibers) exhibited the optimum performance, achieving an ultimate load of 225 kN, which is 18% higher than the control beam, along with 50% greater mid-span deflection, confirming enhanced load-carrying capacity and ductility.
- The graded hybrid beams exhibited multiple fine and well distributed cracks with reduced widths and uniform spacing, highlighting effective stress redistribution and superior crack control compared to plain HPC beams that failed abruptly after first cracking.
- The finite element analysis performed using the Simplified Concrete Damage Plasticity (SCDP) model accurately captured the experimental load–deflection and stress–strain responses, with deviations less than 5%, thereby validating the accuracy and reliability of the developed FE model for hybrid fiber-reinforced high-performance systems.

Overall, the findings demonstrate that functionally graded hybrid fiber-reinforced HPC beams can achieve superior flexural strength, stiffness, and ductility while reducing overall fiber content, making them a material-efficient fiber utilization strategy and sustainable alternative for structural applications requiring high performance and durability. It is noted that the present experimental program did not include full-depth fiber-reinforced concrete beams for direct comparison; however, the effectiveness of functional fiber gradation relative to conventional HPC beams has been clearly demonstrated, and comparative studies with full-depth FRC are recommended as future work. The assumption of perfect bond between fibers and concrete may slightly overestimate stiffness in the post-cracking regime. Future numerical studies may incorporate bond–slip interface elements to simulate fiber pull-out mechanisms more realistically. Furthermore, the established experimental–numerical framework provides a robust foundation for future studies on various hybrid fiber combinations, fiber volume fractions, and gradation strategies aimed at optimizing the structural efficiency and durability of advanced concrete composites.

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