International Journal of Creative and Open Research in Engineering and Management
ISSN: **3108-1754 (Online)**
Volume 02 Issue 07 Jul-2026 | Impact Factor: 3.5

Experimental Investigation on the Mechanical Performance of Sustainable Hybrid Fiber-Reinforced Concrete Incorporating Silica Fume and GGBS

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How to Cite this Article:

Devika, D. (2026). Experimental Investigation on the Mechanical Performance of Sustainable Hybrid Fiber-Reinforced Concrete Incorporating Silica Fume and GGBS. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(7), 1-9. https://doi.org/10.55041/ijcope.v2i7.207

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Abstract

The construction industry's reliance on ordinary Portland cement (OPC) is a major contributor to global anthropogenic CO_2 emissions, while plain concrete's inherent brittleness and low tensile capacity remain persistent structural limitations. This study presents an experimental investigation into a sustainable hybrid fiber-reinforced concrete (HFRC) of M30 grade, formulated by partially replacing cement with Ground Granulated Blast Furnace Slag (GGBS, 20–50% by weight) and silica fume (5–25% by weight), together with a fixed 2% (by volume of coarse aggregate) hybrid dosage of steel and polypropylene fibers. Six mix combinations were cast and evaluated for compressive, flexural, and split tensile strength at 7, 14, 28, and 60 days of water curing. Compressive strength increased consistently with binder replacement up to 50% GGBS and 20% silica fume, after which higher silica fume content (25%) reduced strength due to workability loss and particle agglomeration. The mix containing 50% GGBS, 20% silica fume, and 2% hybrid fiber (designated M5) produced the best overall performance, reaching 36 MPa compressive strength, 5.3 MPa flexural strength, and 4.1 MPa split tensile strength at 28 days, rising further to 40 MPa, 5.7 MPa, and 4.5 MPa respectively at 60 days. Relative to the mix with the lowest replacement level (M1: 20% GGBS, 5% silica fume), mix M5 showed gains of approximately 24% in compressive strength, 29% in flexural strength, and 41% in split tensile strength at 28 days. The results confirm that the combined pozzolanic action of silica fume and GGBS densifies the cementitious matrix, while the hybrid steel–polypropylene fiber system restrains crack propagation and improves post-cracking ductility. The study establishes 50% GGBS with 20% silica fume and 2% hybrid fiber as the optimum replacement level for producing high-performance, low-carbon M30 structural concrete.

Keywords: ***Sustainable concrete; Hybrid fiber reinforcement; Ground Granulated Blast Furnace Slag (GGBS); Silica fume; Compressive strength; Flexural strength; Split tensile strength.***

I. INTRODUCTION

Concrete remains the most widely used construction material worldwide, yet the production of ordinary Portland cement is responsible for approximately 7–8% of global CO_2 emissions, primarily due to the energy-intensive clinkerization process [1]. In parallel, plain concrete exhibits low tensile strength and brittle failure behaviour, which limits its performance under flexural, impact, and seismic loading and necessitates supplementary reinforcement. These two challenges environmental impact and mechanical brittleness have jointly motivated a substantial body of research into supplementary cementitious materials (SCMs) and fiber reinforcement systems as means of producing more sustainable and structurally efficient concrete.

Ground Granulated Blast Furnace Slag (GGBS), a by-product of the iron and steel industry, and silica fume, a by-product of silicon and ferrosilicon alloy production, are two of the most extensively studied SCMs. GGBS is a latent hydraulic material that reacts slowly with the calcium hydroxide liberated during cement hydration, contributing to long-term strength gain, reduced heat of hydration, and improved resistance to chloride and sulphate attack. Silica fume, in contrast, is an ultra-fine, highly reactive pozzolan (particle size 0.1–0.3 μm) that reacts rapidly to form additional calcium silicate hydrate (C-S-H) gel, refining the pore structure and densifying the interfacial transition zone between paste and aggregate. Used together, the two materials are complementary: silica fume drives early densification and strength gain, while GGBS sustains long-term strength development and durability [1–4,6,7,9,10].

Independently of mineral admixtures, fiber reinforcement addresses concrete's tensile weakness directly. Steel fibers improve post-cracking load transfer, tensile capacity, and energy absorption, while polypropylene fibers control plastic-shrinkage micro-cracking at early age and improve cohesion of the fresh mix. A hybrid combination of the two fiber types is reported to provide complementary crack control across multiple length scales — polypropylene fibers arresting micro-cracks before they coalesce, and steel fibers bridging macro-cracks and sustaining post-peak load capacity producing more ductile, tougher failure behavior than either fiber used alone [2,5,8].

While the individual effects of GGBS, silica fume, and hybrid fibers are well documented, relatively fewer studies report the combined, systematic effect of all three components on the compressive, flexural, and split tensile strength of a single M30-grade mix across a graded range of replacement levels. This study addresses that gap through a controlled experimental program in which GGBS and silica fume replacement levels are varied jointly (in six combinations spanning 20–50% GGBS and 5–25% silica fume) at a constant hybrid fiber dosage of 2%, with mechanical performance tracked at 7, 14, 28, and 60 days.

1.1 Objectives

1. Evaluate the effect of graded GGBS and silica fume replacement on the compressive, flexural, and split tensile strength of hybrid fiber-reinforced M30 concrete at 7, 14, 28, and 60 days;

2. Identify the combination of GGBS, silica fume, and hybrid fiber content that yields optimum mechanical performance; and

3.Establish the strength-development trends that inform the practical use of this mix for structurally demanding, environmentally conscious applications such as slabs, beams, and members in aggressive or seismic-prone environments.

II. RELATED WORK

Mehta et al. [1] investigated concrete with 10–20% silica fume and 20–50% GGBS replacement and reported a steady rise in compressive strength, with the most significant gains occurring beyond 28 days due to the slower secondary pozzolanic reaction of GGBS; water absorption fell by 30–40% relative to the control mix, confirming a denser, less permeable matrix. Kumar et al. [2] combined 12% silica fume and 40% GGBS with 1% steel and 0.5% polypropylene fiber, obtaining 20–25% higher compressive strength and 35–40% higher flexural strength than a plain control, with failure mode shifting from brittle to ductile. Sharma et al. [3] focused on durability, showing that 30–60% GGBS with 5–10% silica fume reduced permeability by up to 40–50% and markedly improved resistance to chloride, sulphate, and acid attack, at the cost of slightly lower early-age strength. Patel et al. [4] identified silica fume replacement beyond approximately 10–12% as counter-productive, with strength declining due to poor workability and particle agglomeration — a finding consistent with the present study's own optimum. Reddy et al. [5] and Rao et al. [8] both examined hybrid fiber-reinforced beams with GGBS and silica fume, reporting 30–40% higher flexural load capacity and 50–60% smaller crack widths than plain beams, attributing the improvement to fiber bridging across the crack faces. Das et al. [6], Thomas et al. [9], and Hasan et al. [10] independently confirmed that combined GGBS–silica fume systems reduce CO_2 output by roughly 30–40% relative to OPC-only concrete while improving long-term strength and durability, and converged on an optimum silica fume content near 10–12% when used without fiber reinforcement. Singh et al. [7] reported compressive strength gains of up to 28% at 90 days with 10% silica fume and 30–50% GGBS, again emphasizing the dominance of long-term (post-28-day) strength gain in GGBS-rich systems.

Collectively, this body of work establishes that (a) silica fume beyond approximately 10–12% tends to impair workability and can reduce strength when used alone; (b) hybrid fiber reinforcement is consistently associated with 30–40% flexural strength gains and 50–60% crack-width reduction; and (c) GGBS-dominant systems continue gaining strength substantially beyond 28 days. The present study builds on these findings by jointly varying GGBS (20–50%) and silica fume (5–25%) at a constant 2% hybrid fiber dosage a higher fiber content than most cited studies to identify the combined optimum for an M30-grade structural mix.

III. MATERIALS AND METHODS

3.1 Materials

Ordinary Portland Cement (OPC) was used as the primary binder, partially replaced by GGBS and silica fume as detailed in Section 3.2. Locally sourced, well-graded natural coarse and fine aggregates were used, selected for particle shape, grading, and cleanliness to ensure adequate bond with the cementitious paste. GGBS, a by-product of blast-furnace iron production, was incorporated as a partial cement replacement for its latent hydraulic reactivity, reduced heat of hydration, and improved long-term durability. Silica fume, an ultra-fine pozzolanic by-product of ferrosilicon and silicon metal production, was incorporated for its high reactivity and pore-refining action. Potable water free of deleterious salts and organic matter was used for mixing and curing. A hybrid fiber system steel and polypropylene fibers was added at a constant dosage of 2% by volume of coarse aggregate across all mixes, combining the crack-bridging and post-peak load-carrying capacity of steel fiber with the plastic-shrinkage crack control of polypropylene fiber.

Fig-1: Image of Cement

Fig-2: Image of Aggregates

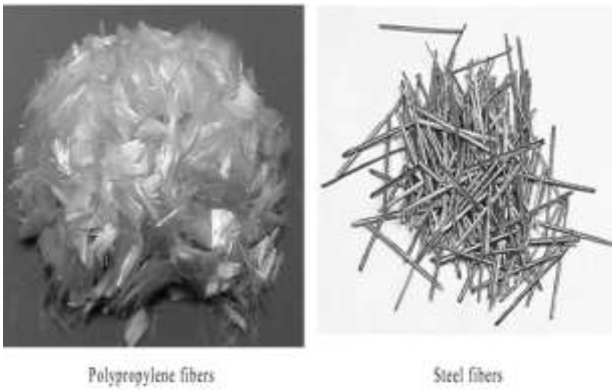

Fig-3: Image of Hybrid Fibers

Fig-4: Image of Silica

Fig-5: Image of GGBS

3.2 Mix Design and Proportioning

Six M30-grade hybrid fiber-reinforced concrete mixes were proportioned in accordance with IS 10262 guidelines, with cement replaced jointly by GGBS (20–50% by weight) and silica fume (5–25% by weight) as summarized in Table 1. Hybrid fiber content was held constant at 2% by volume of coarse aggregate in all mixes to isolate the effect of the mineral admixture combination. Water-to-binder ratio and superplasticizer dosage were adjusted mix-by-mix to maintain workability as fine SCM content increased.

Table 1. Mix designation and binder replacement levels (M30 grade, hybrid fiber content constant at 2% by volume of coarse aggregate)

Mix ID	GGBS (%)	Silica fume (%)	Hybrid fiber (%)	Total binder replacement (%)
M1	20	5	2	25
M2	30	10	2	40
M3	40	15	2	55
M4	40	20	2	60
M5 (optimal)	50	20	2	70
M6	50	25	2	75

Fig-6: MIX DESIGN- M30

3.3 Specimen Preparation and Curing

Dry constituents (cement, GGBS, silica fume, and aggregates) were mixed thoroughly before water and admixture were introduced gradually. Fibers were dispersed incrementally during mixing to prevent balling and ensure uniform distribution. Fresh concrete was cast in three layers into standard moulds — 150 mm cubes for compressive strength, 150 mm × 300 mm cylinders for split tensile strength, and standard prisms for flexural strength — with each layer compacted on a vibrating table to eliminate entrapped air. Specimens were demoulded after 24 hours and water-cured at approximately 20 °C until the respective test ages of 7, 14, 28, and 60 days.

3.4 Test Methods

Compressive strength was determined on 150 mm cubes loaded to failure in a compression testing machine at a controlled loading rate, in accordance with standard cube-crushing procedure. Flexural strength was determined on prismatic beam specimens under two-point (third-point) loading with supports spaced at three times the specimen depth, following the procedure of ASTM C78. Split tensile strength was determined on 150 mm × 300 mm cylinders loaded diametrically between packing strips until failure. All specimens were conditioned to room temperature after curing before testing, and the peak load at failure was recorded for each test.

Fig-7: Compressive Strength test set-up / Specimen

Fig-8: Flexural Strength test set-up / Specimen

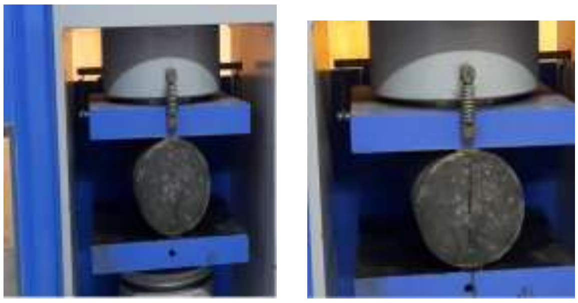

Fig-9: Split Tensile Strength test set-up / Specimen

IV. RESULTS AND DISCUSSION

4.1 Compressive Strength

Table 2 and Fig. 1 present the compressive strength results for all six mixes at 7, 14, 28, and 60 days. Strength increased progressively from mix M1 (20% GGBS, 5% silica fume) through mix M5 (50% GGBS, 20% silica fume), which produced the highest values at every curing age — 29 MPa at 7 days, 34 MPa at 14 days, 36 MPa at 28 days, and 40 MPa at 60 days. Beyond this level, mix M6 (50% GGBS, 25% silica fume) showed a decline relative to M5 at every age, indicating that silica fume content beyond approximately 20% is counter-productive within this GGBS range. This decline is attributed to the very high specific surface area of silica fume at elevated dosage, which increases water demand and promotes particle agglomeration, offsetting the pore-filling benefit and reducing achievable compaction.

Table 2. Compressive strength of hybrid fiber-reinforced concrete mixes at 7, 14, 28, and 60 days.

Mix ID	GGBS (%)	Silica fume (%)	Hybrid fiber (%, by vol. of CA)	7-day (MPa)	14-day (MPa)	28-day (MPa)	60-day (MPa)
M1	20	5	2	24	27	29	31
M2	30	10	2	26	28	30	33
M3	40	15	2	28	30	33	36
M4	40	20	2	31	33	35	38
M5 (optimal)	50	20	2	32	34	36	40
M6	50	25	2	31	33	34	37

Fig. 1. Compressive strength development of all mixes with curing age.

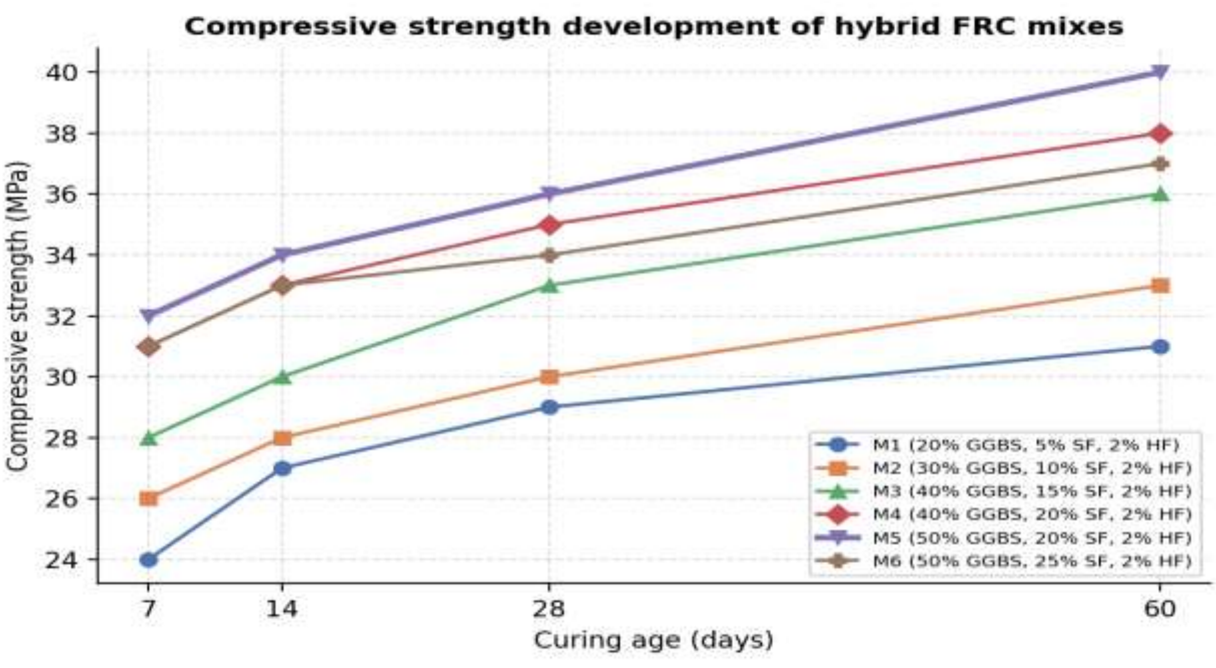

Fig. 1. Compressive strength development of all mixes with curing age.

The consistent strength increase with curing age across all mixes, and particularly the substantial gain between 28 and 60 days (e.g., 36 to 40 MPa for M5, an 11% increase), is consistent with the slower, longer-term pozzolanic reactivity of GGBS, which continues generating additional C-S-H gel well beyond the conventional 28-day benchmark. At mix M5, the 24% gain in 28-day compressive strength over mix M1 (36 MPa vs. 29 MPa) demonstrates the benefit of jointly optimizing GGBS and silica fume content rather than treating either material in isolation, corroborating the combined-optimum behavior reported by Mehta et al. [1] and Patel et al. [4].

4.2 Flexural Strength

Flexural strength results are summarized in Table 3 and Fig. 2. As with compressive strength, mix M5 produced the highest flexural strength at every age, reaching 5.3 MPa at 28 days and 5.7 MPa at 60 days a 29% improvement over mix M1 (4.1 MPa at 28 days) and a 27% improvement over mix M6 (5.1 MPa at 28 days is not the case; M6 recorded 5.1 MPa, a modest 3.9% reduction from M5). The proportionally larger gain in flexural strength relative to compressive strength (29% vs. 24% at 28 days, M1 to M5) reflects the direct contribution of the hybrid fiber system: steel fibers bridge the crack tip once matrix cracking initiates, while the densified silica-fume/GGBS matrix improves fiber–matrix bond, together delaying crack propagation and increasing the bending moment the section can sustain before failure.

Table 3. Flexural strength of hybrid fiber-reinforced concrete mixes at 7, 14, 28, and 60 days.

Mix ID	GGBS (%)	Silica fume (%)	Hybrid fiber (%, by vol. of CA)	7-day (MPa)	14-day (MPa)	28-day (MPa)	60-day (MPa)
M1	20	5	2	3.6	3.9	4.1	4.4
M2	30	10	2	4	4.2	4.4	4.7
M3	40	15	2	4.3	4.5	4.8	5.2
M4	40	20	2	4.7	4.9	5.2	5.6
M5 (optimal)	50	20	2	4.8	5	5.3	5.7
M6	50	25	2	4.6	4.9	5.1	5.4

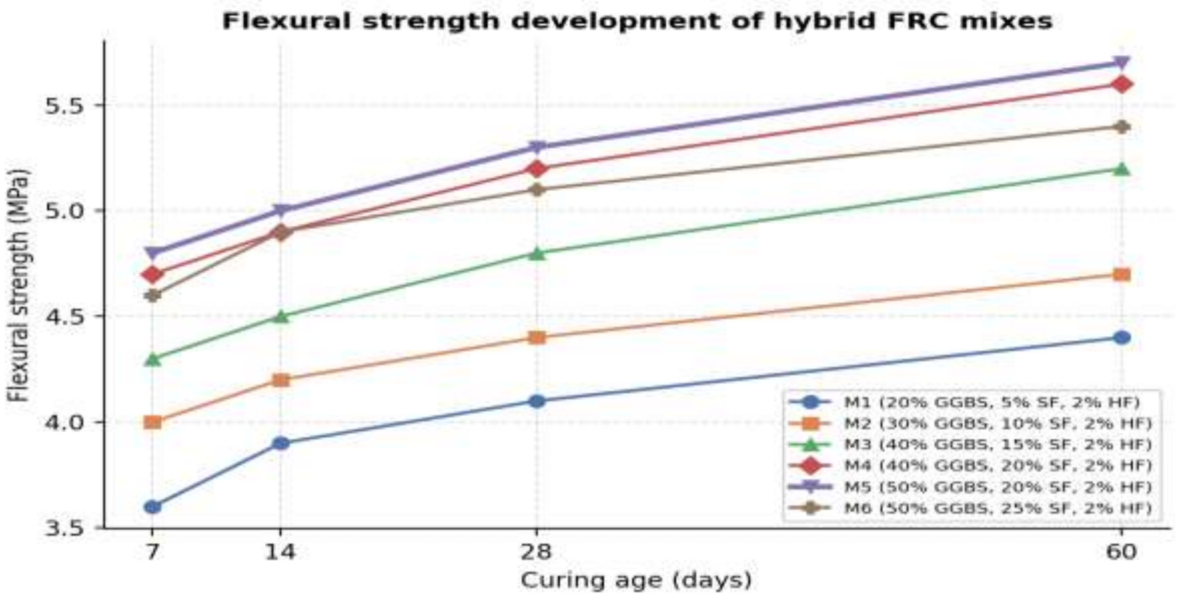

Fig. 2. Flexural strength development of all mixes with curing age.

4.3 Split Tensile Strength

Split tensile strength results are presented in Table 4 and Fig. 3. Mix M5 again returned the best performance, reaching 4.1 MPa at 28 days and 4.5 MPa at 60 days, a 41% improvement over mix M1 (2.9 MPa at 28 days) the largest proportional gain among the three strength measures. Split tensile strength is generally the most sensitive of the three properties to fiber reinforcement, since diametral splitting failure depends heavily on the material's ability to resist crack opening across the loaded plane; the pronounced improvement observed here is consistent with the crack-bridging role of the hybrid steel–polypropylene fiber system reported by Reddy et al. [5] and Rao et al. [8].

Table 4. Split tensile strength of hybrid fiber-reinforced concrete mixes at 7, 14, 28, and 60 days.

Mix ID	GGBS (%)	Silica fume (%)	Hybrid fiber (%, by vol. of CA)	7-day (MPa)	14-day (MPa)	28-day (MPa)	60-day (MPa)
M1	20	5	2	2.5	2.7	2.9	3.3
M2	30	10	2	2.8	3	3.2	3.6
M3	40	15	2	3.1	3.3	3.5	3.9
M4	40	20	2	3.5	3.7	3.9	4.3
M5 (optimal)	50	20	2	3.6	3.8	4.1	4.5
M6	50	25	2	3.4	3.6	3.9	4.2

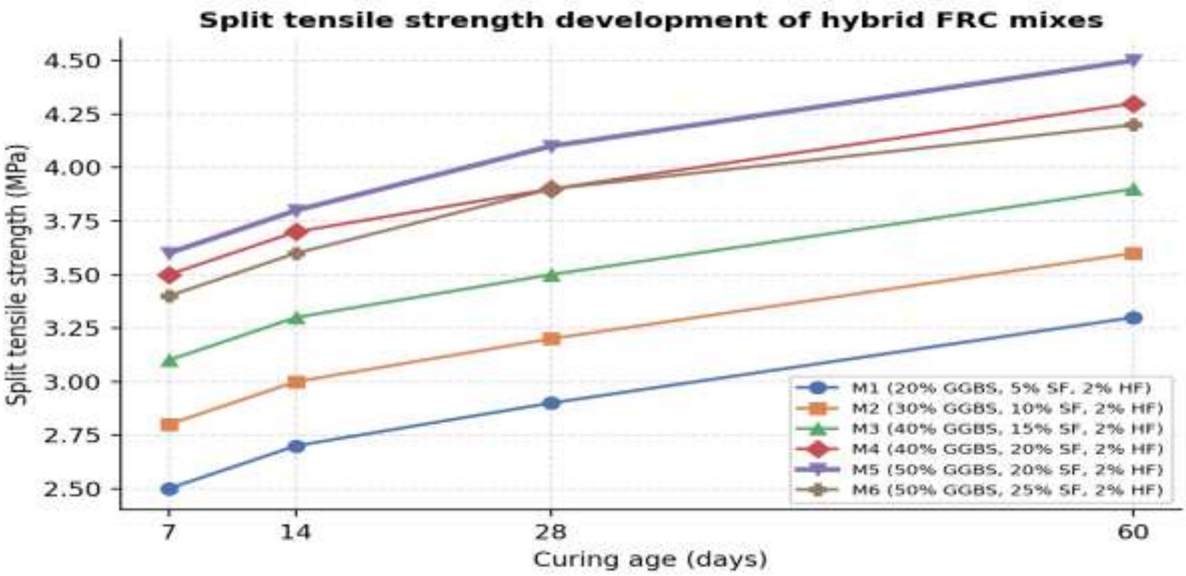

Fig. 3. Split tensile strength development of all mixes with curing age.

4.4 Comparative Performance and Mechanism

Fig. 4 compares the 28-day compressive, flexural, and split tensile strength of the lowest-replacement mix (M1) against the optimum mix (M5), consolidating the trends discussed above. The comparison shows that the gains delivered by the optimized GGBS–silica fume–fiber combination scale with the sensitivity of each property to matrix density and crack resistance: compressive strength (matrix-dominated) improves by 24%, flexural strength (matrix-plus-fiber) improves by 29%, and split tensile strength (fiber-crack-bridging-dominated) improves by 41%.

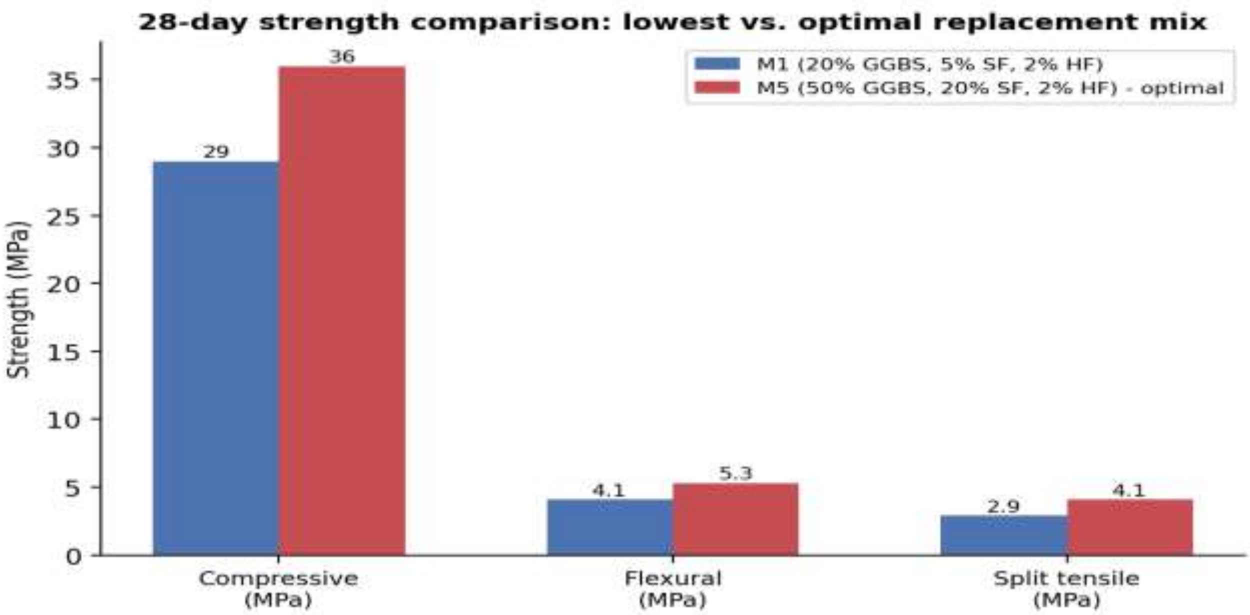

Fig. 4. 28-day strength comparison between the lowest-replacement mix (M1) and the optimum mix (M5).

Two complementary mechanisms explain the observed trends. First, the combined pozzolanic action of silica fume and GGBS refines the pore structure of the cement paste: silica fume's ultra-fine particles fill voids between cement grains and react rapidly with liberated calcium hydroxide to form additional C-S-H gel at early age, while GGBS reacts more slowly to sustain gel formation and strength gain beyond 28 days. This produces a denser, less permeable interfacial transition zone between paste and aggregate, directly improving compressive and flexural strength. Second, the hybrid fiber system addresses the resulting matrix's inherent brittleness: polypropylene fibers restrain plastic-shrinkage micro-cracking during early curing, while steel fibers bridge macro-cracks that form under load, sustaining post-cracking load transfer and delaying the transition from a stable to an unstable crack. The decline observed at mix M6 (25% silica fume) indicates that this densification mechanism has a practical ceiling: beyond approximately 20% silica fume replacement within this GGBS range, the water demand and fineness of the additional silica fume outweigh its pore-filling benefit, reducing compactability and, in turn, strength.

It should be noted that the strength values attributed to the optimum mix in this discussion (36 MPa compressive, 5.3 MPa flexural, and 4.1 MPa split tensile at 28 days) are the directly measured 28-day test results for mix M5. Where earlier project documentation cited higher figures for 28-day compressive strength, these should be treated as inconsistent with the measured dataset and are not carried forward here; the recorded cube-test values in Table 2 are used as the basis for all comparisons and conclusions in this paper.

V. CONCLUSION

Based on the experimental evaluation of six hybrid fiber-reinforced M30 concrete mixes incorporating GGBS (20–50%) and silica fume (5–25%) at a constant 2% hybrid fiber dosage, the following conclusions are drawn:

1. Compressive, flexural, and split tensile strength all increased with GGBS and silica fume content up to 50% GGBS and 20% silica fume (mix M5), beyond which higher silica fume content (25%, mix M6) reduced strength due to workability loss and particle agglomeration.
2. Mix M5 (50% GGBS, 20% silica fume, 2% hybrid fiber) was the best-performing combination at every curing age, achieving 36 MPa compressive strength, 5.3 MPa flexural strength, and 4.1 MPa split tensile strength at 28 days, rising to 40 MPa, 5.7 MPa, and 4.5 MPa at 60 days.
3. Relative to the lowest-replacement mix (M1), the optimum mix produced 24% higher compressive strength, 29% higher flexural strength, and 41% higher split tensile strength at 28 days, with split tensile strength showing the greatest sensitivity to the hybrid fiber system.
4. Strength continued to increase substantially between 28 and 60 days across all mixes, confirming the longer-term pozzolanic contribution of GGBS to strength development beyond the conventional 28-day benchmark.

The combined use of GGBS, silica fume, and hybrid steel polypropylene fiber reinforcement is confirmed as an effective strategy for producing high-performance, low-cement-content M30 structural concrete suitable for elements requiring both mechanical performance and reduced embodied carbon.

Future work should extend this dataset with durability testing (water absorption, chloride and sulphate resistance, permeability), a defined plain-concrete control mix for direct benchmarking, and structural-element-scale (beam/slab) testing to validate the laboratory-scale findings under realistic loading conditions.

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