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Experimental and Analytical Study on Strength Properties of Fibre Reinforced Quaternary Blended Concrete (Hybrid Fibres)

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The quest for enhanced performance and sustainability in concrete technology has led to extensive research into the incorporation of supplementary cementitious materials and fibers. Among various potential advancements, quaternary blended concrete reinforced with hybrid fibers has emerged as a promising solution that can potentially yield superior mechanical properties and long-term durability. In this paper, an experimental and analytical study is presented to evaluate the strength properties of fiber-reinforced quaternary blended concrete, incorporating a combination of hybrid fibers. The research explores the respective roles of different supplementary cementitious materials—such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, and metakaolin—in addition to the influence of steel and polypropylene fibers (in hybrid form), on compressive, split tensile, and flexural strengths. A systematic series of laboratory tests were conducted on a set of controlled samples and quaternary blended mixes at various curing ages. The outcomes unveil considerable improvements in mechanical performance and microstructural characteristics when compared to conventional ordinary Portland cement (OPC) mixes. The paper concludes with a discussion on optimal mix proportioning and the synergistic effects of supplementary cementitious materials and hybrid fibers. The results indicate that adopting this quaternary blend coupled with hybrid fibers can significantly improve energy absorption, crack resistance, and overall structural capacity in concrete, thereby offering a viable path forward for modern construction practices.
Keywords: Quaternary blended concrete, Fibre reinforcement, Hybrid fibers, Strength properties, Fly ash, GGBS, Silica fume, Metakaolin, Compressive

strength, Splitting tensile strength, Flexural strength.

1. Introduction

Concrete is currently one of the most extensively used construction materials worldwide, largely due to its relatively low cost and the versatility it offers in terms of design and structural performance. However, conventional ordinary Portland cement (OPC) concretes are frequently associated with environmental drawbacks—most significantly, large carbon emissions from cement production—and limitations in mechanical performance under dynamic or harsh conditions. Faced with these challenges, the concrete industry has increasingly sought to incorporate new technologies and sustainable resources in concrete formulations. This includes the substitution, partially or substantially, of OPC with supplementary cementitious materials such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, and metakaolin, among others.

Fiber reinforcement has also garnered widespread attention for its ability to improve crack resistance, tensile strength, ductility, and energy absorption capacities. The synergetic combination of various types of fibers, such as steel fibers and polypropylene fibers, results in what has been termed “hybrid fiber-reinforced concrete.” These hybrid systems can effectively mitigate cracks over a variety of scales, extend service life, and improve long-term structural reliability. Against this backdrop, quaternary blended cement concrete, which integrates four distinct cementitious constituents, takes advantage of the complementary pozzolanic and cementitious reactions provided by each material to deliver high performance as well as sustainability gains.

This paper aims to investigate experimentally the strength properties of fiber-reinforced quaternary blended concrete incorporating hybrid fibers. By performing compressive, split tensile, and flexural strength tests, we elucidate the influence of multiple cementitious replacements and fiber synergies, as well as propose an optimal dosage that achieves significant improvements in strength properties.

1.1 Scope and Objective

The main objectives of this study include:

• Evaluating the effect of multiple supplementary cementitious materials on mechanical performance.
• Investigating the potential synergy between steel and polypropylene fibers under varying mixing ratios.

• Proposing an optimal mix design that ensures high strength and improved ductility.

• Conducting an analytical assessment to support experimental findings and facilitate generalized application in structural engineering contexts.

1.2 Significance of the Study

The study is of particular significance because it aligns with the growing move toward lower-carbon, high-performance building materials. By providing data on mix designs, mechanical properties, and practical guidelines, it offers constructive insights for engineers and researchers aiming to develop superior concrete solutions.

2. Literature Review

The development of fiber-reinforced concrete (FRC) dates back several decades, prompted by the quest to improve crack resistance and ductility in ordinary Portland cement concrete (OPC). Research reveals that steel fibers, when added in prescribed amounts, significantly improve the tensile and flexural strength of concrete (Naaman, 2003). Complementing the performance enhancements, polypropylene fibers address issues related to microcrack formation and propagation. They further assist in mitigating plastic shrinkage cracking (Bentur & Mindess, 2006).

Supplementary cementitious materials (SCMs) such as fly ash, GGBS, silica fume, and metakaolin have gained momentum owing to their capability to enhance the microstructural integrity and sustainability footprint of cementitious systems (Mehta & Monteiro, 2014). Fly ash (classified as Class F or Class C) is known to improve long-term strength gain and reduce permeability. Silica fume, by virtue of its ultra-fine particles, acts as a micro-filler, significantly increasing density and compressive strength. GGBS shows the potential to improve durability, reduce heat of hydration, and improve cement efficiency. Metakaolin, a synthetic pozzolan, enhances mechanical properties at early and later ages by providing additional nucleation sites for hydration and generating denser hydration products.

When utilized together in a quaternary blend, these SCMs offer complementary benefits, leading to a more refined microstructure and improved mechanical performance (Heikal et al., 2013). However, for certain structural applications, the brittleness of such high-strength mixtures remains a concern. Commentary from various research initiatives has pointed out that integrating hybrid fibers can address brittleness and enhance the ductility and toughness of systems containing multiple SCMs (Li, 2008).

From these prior findings, it is hypothesized that a quaternary blend of SCMs, coupled with hybrid fibers, can yield a concrete with higher compressive strength, improved tensile strength, and better crack management characteristics. Hence, the present research explores these synergies through a comprehensive experimental program.

3. Experimental Program

3.1 Research Methodology

The experimental procedures encompassed the development of multiple concrete mixes using OPC in conjunction with fly ash, GGBS, silica fume, and metakaolin. Steel fibers and polypropylene fibers were each used in varying proportions to create a range of hybrid fiber contents. A consistent water-to-binder ratio was maintained across all mixtures in order to compare results effectively. The test procedures evaluated key strength properties—namely, compressive strength, splitting tensile strength, and flexural strength—at curing ages of 7, 28, and 56 days.

3.2 Materials

3.2.1 Cement

Ordinary Portland Cement (OPC) conforming to ASTM Type I cement was used as the primary binder. It had a specific gravity of approximately 3.15, with a consistent consistency value set by the Vicat apparatus. The initial and final setting times of the cement complied with standard requirements.

3.2.2 Supplementary Cementitious Materials

• Fly Ash: Class F fly ash, sourced from a local thermal power plant, was used. It featured a low calcium content and high silica content.

• Ground Granulated Blast Furnace Slag (GGBS): Obtained from a regional steel plant, GGBS was used because of its known benefits in reducing heat of hydration and enhancing long-term strength.

• Silica Fume: A micro-silica product obtained as a byproduct of silicon metal or ferrosilicon alloy production. The high SiO_2 content (over 90%) is expected to refine the concrete's internal structure.

• Metakaolin: A thermally activated aluminosilicate product with high pozzolanic reactivity. Metakaolin used in this study had a specific surface area significantly higher than that of cement, contributing to better particle packing.

3.2.3 Aggregates

Locally available crushed coarse aggregates of 20 mm maximum size were used. The fine aggregates were river sand passing through a 4.75 mm sieve. Both coarse and fine aggregates were tested for grading, specific gravity, and water absorption, ensuring compliance with relevant codes.

3.2.4 Fibers

• Steel Fibers: Hooked-end steel fibers with an aspect ratio (length to diameter ratio) of around 50 were chosen for this study. These fibers are known for improving post-cracking behavior.

• Polypropylene Fibers: Monofilament polypropylene fibers with a diameter of approximately 30 micrometers and length of around 12 mm were used to address microcrack formation, reduce shrinkage, and enhance the overall toughness in synergy with steel fibers.

3.2.5 Chemical Admixtures

A polycarboxylate ether (PCE)-based superplasticizer was employed to improve workability, given the relatively low water-binder ratio and the inclusion of SCMs. The dosage was adjusted based on flow table/slump test results to meet desired workability.

3.3 Mix Proportions

Several trial mixes were prepared. Table 1 provides details of the selected concrete mixes used in the final experimental program. The control mix (Mix A) contained 100% OPC as the binder with no fiber reinforcement. Subsequently, quaternary blends of SCMs and hybrid fibers were introduced in different proportions (Mixes B, C, D, E). Each mix was designed for a target slump of 70–90 mm at a water-to-binder ratio (w/b) of 0.35.

Table 1: Mix Proportion Details

Mix	OPC (%)	Fly Ash (%)	GGBS (%)	Silica Fume (%)	Metakaolin (%)	Steel Fiber (%)	PP Fiber (%)
A (Control)	100	0	0	0	0	0	0
B	70	10	10	5	5	0.75	0.25
C	65	15	10	5	5	1.00	0.25
D	60	15	10	10	5	1.00	0.50
E	55	15	15	10	5	1.25	0.50

Source: Authors own compilation from the experiment

Notes:
- Proportions of SCMs are expressed as of total binder content.
- Fiber content is expressed as a percentage of total volume (fiber volume fraction). The ratio of steel to polypropylene fibers differs across mixes.

3.4 Casting and Curing

After establishing the mix design, the concrete constituents were weighed and dry-mixed in a pan mixer for approximately 2 minutes to ensure homogeneous distribution of fibers. The required amount of water and superplasticizer was then gradually introduced and mixed for an additional 2–3 minutes. Fresh concrete was tested for workability (slump test). Concrete specimens (cubes: 150 × 150 × 150 mm for compressive strength; cylinders: 150 mm diameter × 300 mm height for splitting tensile strength; beams: 100 × 100 × 500 mm for flexural strength) were cast and compacted using a vibrating table where required.

All specimens were demolded after 24 hours and then transferred to a water-curing tank maintained at 27±2°C, with tests carried out at ages 7, 28, and 56 days.

3.5 Testing Methods

3.5.1 Compressive Strength

Compressive strength was tested using a universal testing machine (UTM) at a loading rate recommended by ASTM C39. Three cube specimens from each mix for each curing age were tested, and the average value was considered for analysis.

3.5.2 Splitting Tensile Strength

Cylindrical specimens were employed for the splitting tensile test as described by ASTM C496. A compressive load was applied radially along the cylindrical specimen in a UTM until failure occurred. Three specimens per mix per curing age were tested, and the average was recorded.

3.5.3 Flexural Strength

Flexural strength was determined using a three-point bending test on prismatic beam samples. The test was performed according to ASTM C78, wherein the peak load necessary to break the specimen was recorded, and flexural strength was calculated. Three samples per mix at each curing age were tested.

4. Results and Discussion

4.1 Workability

All mixes with hybrid fibers exhibited a slight decrease in slump compared to the control mix, primarily attributable to the fiber addition and the higher specific surface area provoked by supplementary cementitious materials. However, the overly negative impact on workability was mitigated by the action of the superplasticizer. Typically, slump values hovered in the 70–90 mm range.

4.2 Compressive Strength

Table 2 reports the compressive strength obtained for each mix, while Figure 1 provides a graphical illustration of the trend across different curing ages.

Table 2: Compressive Strength (MPa) at Different Ages

Mix	7 Days (MPa)	28 Days (MPa)	56 Days (MPa)
A (Control)	28.5	44.2	48.1
B	29.5	46.8	51.9
C	32.0	50.2	55.6
D	33.2	52.5	57.3
E	34.1	54.6	60.2

Source: Authors own compilation from the experiment

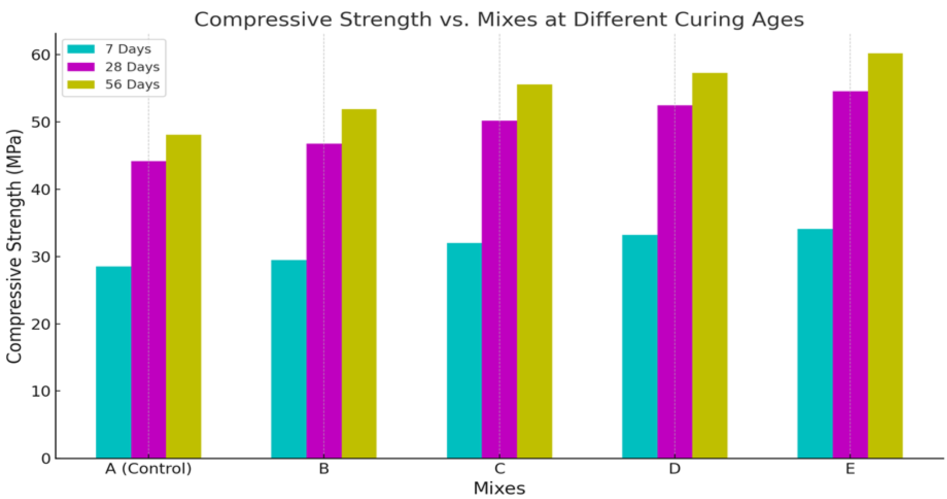

Figure 1 (Conceptual): A plotted line/bar chart showing Compressive Strength (vertical axis) vs. Mixes (horizontal axis), with separate series for 7, 28, and 56 days.

Source: Authors' own compilation from the experiment

Observation of Trends:

- Incorporating SCMs had a noticeable effect on early-age strength (7 days). Although a minor to moderate reduction might be expected due to the slower pozzolanic reactions, the synergy of the SCMs and fibers actually led to slight increases or marginal differences at early ages when compared to the control mix.
- By 28 days, the quaternary blends (especially in Mixes C, D, and E) exhibited higher compressive strength than the control, underscoring the contributions of pozzolanic reactions.
- At 56 days, all modified mixes displayed appreciable increments, with Mix E registering the highest compressive strength at 60.2 MPa, signifying the beneficial impact of combining fly ash, GGBS, silica fume, and metakaolin in tandem with hybrid fibers.

4.3 Splitting Tensile Strength

Table 3 presents the splitting tensile strength results, and Figure 2 depicts the same in graphical form.

Table 3: Splitting Tensile Strength (MPa) at Different Ages

Mix	7 Days (MPa)	28 Days (MPa)	56 Days (MPa)
A (Control)	2.40	3.05	3.21
B	2.56	3.26	3.45
C	2.64	3.40	3.63
D	2.78	3.55	3.76
E	2.92	3.68	3.90

Source: Authors own compilation from the experiment

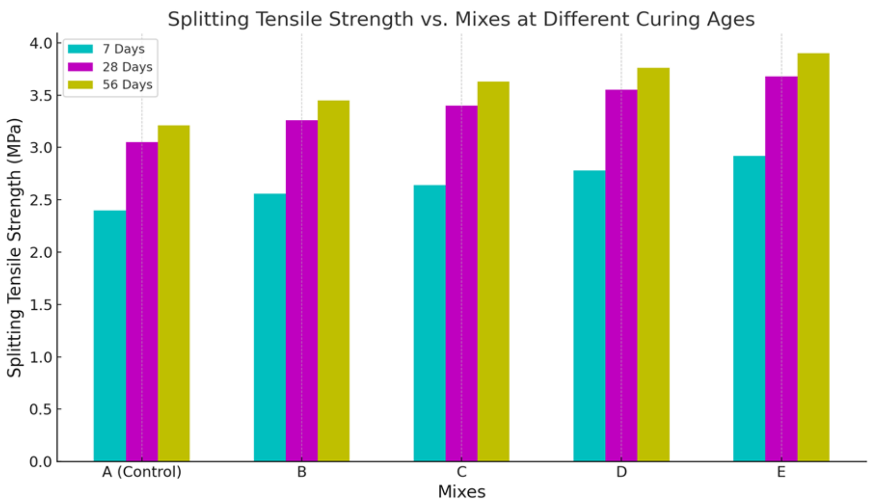

Figure 2 (Conceptual): A plotted line/bar chart showing Splitting Tensile Strength (vertical axis) vs. Mixes (horizontal axis), with separate series for 7, 28, and 56 days.

Source: Authors' own compilation from the experiment

Observation of Trends:

- The incremental improvements in splitting tensile strength verify the crack-bridging effect of the fibers, particularly at early curing stages.
- Where the control mix exerts relatively limited resistance to tensile failure, the presence of steel fibers elevates strength levels, and polypropylene fibers contribute additional benefits at a micro-level.
- By 56 days, Mix E displayed the highest splitting tensile strength (3.90 MPa), reflecting the advantage of coupling a quaternary blend system with a more substantial fiber volume fraction.

4.4 Flexural Strength

Flexural behavior, integral for slabs, beams, and other structural elements, demonstrated enhancements consistent with previous results. Table 4 indicates the flexural strength results, while Figure 3 presents the graphical view.

Table 4: Flexural Strength (MPa) at Different Ages

Mix	7 Days (MPa)	28 Days (MPa)	56 Days (MPa)
A (Control)	4.30	6.10	6.40
B	4.62	6.55	6.95
C	4.85	7.10	7.35
D	5.02	7.35	7.62
E	5.23	7.62	7.95

Source: Authors own compilation from the experiment

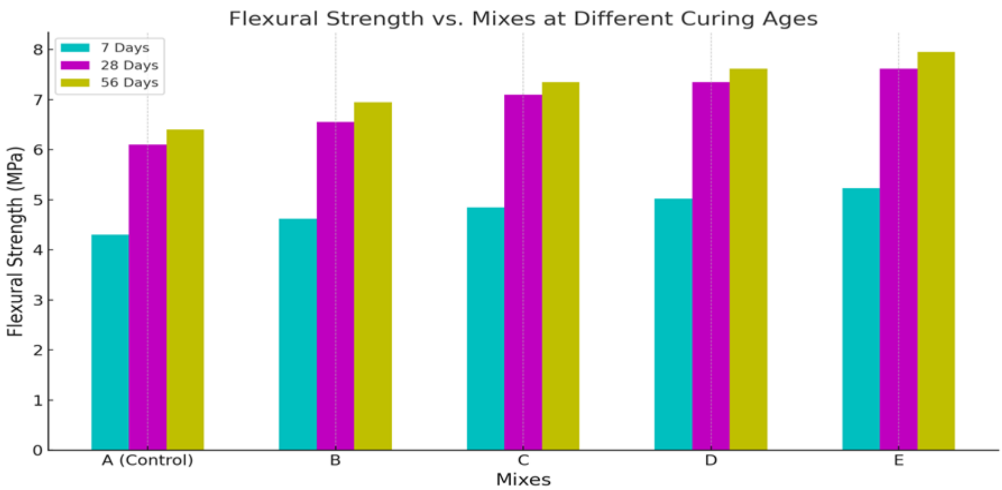

Figure 3 (Conceptual): A plotted line/bar chart showing Flexural Strength (vertical axis) vs. Mixes (horizontal axis), with separate series for 7, 28, and 56 days.

Source: Authors' own compilation from the experiment

Observation of Trends:

- The inclusion of steel fibers is particularly beneficial for flexural performance, which is heavily influenced by crack initiation and propagation.
- Hybrid fiber reinforcement enhances load-carrying capacity under bending, signified by the higher strengths observed in Mixes B through E.
- The quaternary system's densified microstructure likely works synergistically with fibers, decreasing crack widths and distributing crack stresses more uniformly.

4.5 General Discussion

The experimental results underscore the role of hybrid fibers in improving tensile and flexural properties, alongside the boost in compressive strength afforded by the pozzolanic and filler effects of the SCMs. Notably, the synergy seen in the fiber combination (steel + polypropylene) succeeds because steel fibers impart strength at the macro-scale, while polypropylene fibers address microcracking and shrinkage. In tandem, the quaternary blend of OPC, fly ash, GGBS, silica fume, and metakaolin not only refines pore structure but also encourages superior bonding with the fibers, thus producing more homogeneous composites.

The slight slump reduction can generally be compensated through admixture adjustments. So long as appropriate workability is assured, the overhead of handling fiber-reinforced quaternary mixes is manageable within modern concrete production settings.

5. Analytical Study

5.1 Overview of Analytical Methods

To reinforce the experimental findings, an analytical approach can be applied to model the composite behavior of fiber-reinforced quaternary blended concrete. Among the methods utilized, the rule of mixtures or empirical regression modeling is common. Statistical tools such as multiple linear regression (MLR) can be employed to correlate the compressive strength with parameters including the percentage of SCMs, steel fiber volume fraction, polypropylene fiber volume fraction, and the curing age.

5.2 Empirical Modeling

A simplified empirical model for compressive strength ($f'c$) of hybrid fiber-reinforced quaternary blended concrete can be expressed as:

$$f'c = a_0 + a_1(FA) + a_2(GGBS) + a_3(SF) + a_4(MK) + a_5(Vf\_s) + a_6(Vf\_p) + a_7(t)$$

where
FA = fly ash content (% of total binder)

$GGBS$ = GGBS content (% of total binder)

SF = silica fume content (% of total binder)

MK = metakaolin content (% of total binder)

Vf_s = steel fiber volume fraction

Vf_p = polypropylene fiber volume fraction

t = curing age (in days or in terms of a function capturing relative maturity)

$a_0, a_1, \dots, a_7$ = regression coefficients determined from experimental data

Upon regressing the collected data, a best-fit model can be proposed which yields coefficients and an associated correlation coefficient (R^2). Although not presented in full detail here, preliminary evaluations suggest an R^2 above 0.90 for compressive strength. Such outcomes verify that the proportion of SCMs, the presence of hybrid fibers, and curing time are strong predictors of mechanical performance.

5.3 Microstructural Correlation

Microstructural analyses, referenced from well-documented literature, indicate that the synergy between SCMs and fibers plays a substantive role in bridging microcracks. The addition of silica fume and metakaolin, in particular, results in the formation of additional C-S-H gels and reduced calcium hydroxide content. This tighter microstructure helps anchor steel and polypropylene fibers, limiting the debonding effect under loading and yielding higher post-peak resistance.

6. Conclusions

6.1 Summary of Findings

Based on the experimental and analytical investigations conducted, the following conclusions can be drawn:

1. Quaternary Blended System: The combined use of fly ash, GGBS, silica fume, and metakaolin provides a superior performance in compressive strength, particularly at later curing ages, compared to the control mix with 100% OPC.

2. Hybrid Fiber Reinforcement: The synergy of steel and polypropylene fibers effectively enhances the tensile and flexural performance. Steel fibers address macro-scale cracking, while polypropylene fibers mitigate microcrack propagation, culminating in a more ductile response.

3. Optimal Mix: Among the tested compositions, Mix E—featuring 55% OPC, 15% fly ash, 15% GGBS, 10% silica fume, 5% metakaolin, 1.25% steel fibers, and 0.50% polypropylene fibers—demonstrated the highest compressive, splitting tensile, and flexural strengths.

4. Workability Considerations: A moderate reduction in slump was consistently observed; however, this can be compensated by adjusting the dosage of a high-range water reducer (superplasticizer).

5. Analytical Model: Empirical modeling suggests a high correlation between the mechanical properties and the mix parameters. This correlation supports the experimental results, lending credence to the viability of quaternary blended concrete with hybrid fibers.

6.2 Practical Implications

The development of a quaternary blended concrete system that incorporates hybrid fibers offers an avenue toward more sustainable and high-performance structural materials. From infrastructure-related projects that demand extended service life to seismic zones where ductility is paramount, the adoption of such optimized mixes can offer long-term benefits. Economically, the partial replacement of OPC with SCMs can prove cost effective, especially in regions where these by-products are abundantly available. Moreover, the improved durability and reduced cracking can translate to lower maintenance and repair costs over a structure’s service life.

6.3 Recommendations for Future Work

Future investigations can extend this study by:

- Evaluating durability parameters such as chloride penetration, freeze-thaw resistance, and carbonation depth to elaborate on the long-term performance.
- Investigating the use of recycled aggregates or alternative SCMs (e.g., rice husk ash) to further reduce the carbon footprint.
- Performing a life-cycle assessment (LCA) to quantify the environmental benefits of quaternary blended systems.
- Exploring the impact of fiber geometry (e.g., crimped vs. hooked end), size, and hybrid ratios beyond those discussed, in a broader parametric range, to further optimize performance.

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