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Investigation for optimal hybrid concrete blended with polypropylene and steel fiber to evaluate structural performance

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ABSTRACT

In recent times, there has been a significant surge in interest regarding the usage of different materials to strengthen concrete. The capacity to enhance the tensile strength of concrete has made Hybrid Fiber Reinforced Concrete (HFRC) a subject of considerable interest. The purpose of this study is to investigate the effect of polypropylene and steel fibers on the strength of concrete. The variable parameters encompass varying proportions of steel and polypropylene fibers. A thorough experimental program, encompassing a total of 36 combinations, was executed with diverse HFRC mixtures. Based on past research, it is projected that fibers would perform better. One combination served as the control, while the other 35 combinations incorporated PPF in varying proportions (ranging from 0.2% to 1% of the cement's mass) with an increment of 0.2%, along with steel fibers (ranging from 0.25% to 3% of the cement's mass). Following this, split tensile strength tests (performed according to ASTM C 496) were carried out. Tensile testing was performed on specimens to observe the failure mode and tensile strength of the samples. The report ends by highlighting the research findings and outlining potential directions for additional study in this area. In conclusion, this study’s findings offer convincing evidence about the use of fibers in concrete.

KEYWORDS: HFRC, Polypropylene, Split tensile strength, Fiber

1 INTRODUCTION

Cementitious materials inherently display brittleness due to their low tensile strength and strain capacity. To address this brittleness and enhance the resistance to fracture initiation and propagation in concrete, short and randomly arranged fibers are frequently employed. The objective is to impede or minimize the initiation, growth, or merging of fractures, thereby achieving an overall improvement in performance. [1]. Fibers can be added to cement-based materials to improve their tensile strength as well as ductility, toughness, and durability. [2]. Concrete engineering commonly utilizes a range of fiber types such as metallic, polymeric, and natural fibers [3].

Typically, traditional fiber-reinforced concrete uses only one type of fiber, limiting its strain and fracture-opening effectiveness. Consequently, a particular fiber type may only contribute to either the strength or ductility improvement of concrete. [4]. While fibers like carbon, polyvinyl alcohol, steel, asbestos, and glass possess high modulus and strength, capable of substantially enhancing the strength of concrete, their inherent brittleness hinders the improvement of concrete's ductility.[5]. Fibers with low strength, such as nylon, acrylic, and polypropylene, excel in enhancing ductility and reducing the occurrence of cracks. [6]. In studies on Hooked End Steel Fiber Concrete, researchers emphasize the superiority of hooked end fibers over straight or crimped shapes due to their unique bridging action. This characteristic enhances the post-cracking behavior of concrete, providing increased strength and durability. The hooked ends effectively interlock within the concrete matrix, improving its ability to resist cracking and enhancing overall structural performance [7][8].

Steel fibers are known for their strong tensile strength and significant impact in controlling crack propagation in concrete structures. Adding steel fibers to concrete enhances its tensile and flexural strength, making it more resilient to dynamic loads and potential structural failures [9][10]. Polypropylene fibers, known for impeding crack formation and reducing plastic shrinkage in concrete, significantly enhance durability. They are crucial in improving toughness and minimizing cracking, particularly in challenging environmental conditions and rapid temperature changes.

To enhance both the ductility and strength of concrete, it is imperative to integrate fibers with varied chemical and mechanical characteristics into cementitious composites. Hybrid Fiber-Reinforced Concrete (HFRC) is achieved through the amalgamation of two or more types of fibers. Combining different fibers proves effective in mitigating cracks at various scales, ranging from micro to macro levels. The blending of these fibers has the potential to enhance both the initial cracking strength and the post-cracking behavior of the concrete simultaneously. Consequently, incorporating multiple fiber types in hybrid FRC results in superior performance compared to individual fibers. The hybrid concrete exhibits a synergistic response, harnessing benefits from each of its component fibers [11][12][13]. A comprehensive literature review supports the notion that blending fibers with diverse chemical and mechanical traits in cementitious composites significantly enhances the concrete's strength, ductility, and toughness [9][14].

Globally, extensive research, development, and application of HFRC are underway, with ongoing progress in fiber-reinforced building materials reflecting industry interest and economic potential. However, increasing the fiber content beyond a certain percentage results in a decline in the tensile strength of HFRC [15][16][17]. Establishing the optimal percentage of fibers is essential for ensuring the effectiveness of HFRC. Few studies have explored the optimal combination of hybrid fibers to enhance the split cylinder tensile strength of HFRC. An experimental study has been conducted to identify the optimal percentage of polypropylene and steel fibers for the hybrid fiber-reinforced concrete mix, aiming to address this gap.

2 MATERIALS

OPC Type II, conforming to ASTM C150, served as the cementitious material for entirely concrete trials in this experiment. It adheres to the ASTM C150 standard. With a specific gravity of 3.03, it showed no expansion in Le-Chattelier's test. The setting time initially took 91 minutes, whereas the final setting time extended to 225 minutes.

The coarse aggregate used in the construction project was sourced locally, specifically from the Pattern Garr crusher. It is comprised of crushed aggregate with a maximum size not exceeding 19 mm. The coarse aggregate has a specific gravity of 2.60 and a water absorption rate of 0.46%. The coarse aggregates exhibit loose and compacted bulk density values of 1437 kg/m³ and 1526 kg/m³, respectively. For the fine aggregate, Lawrencepur-sourced river sand, which is dry and clean and passes through a 4.75-mm sieve, is utilized. The fine aggregate possesses a specific gravity of 2.62 and an absorption rate of water at 0.93%. Its loose and compacted bulk density values are 1600 kg/m³ and 1688 kg/m³, respectively.

In this study, an aqueous modified solution of polycarboxylate-based superplasticizer (Ultra Superplast 470) was employed to attain the desired workability of the Polypropylene and steel fiber-reinforced concrete mixtures. The superplasticizer dosage amounted to 1% of the cement's weight.

The literature review reveals that the selection of fiber size depends on both the length-to-diameter aspect ratio and their tensile strength. The previous study suggests that the aspect ratio's optimal value should fall within the range of 30 to 80. The flexural and compressive strengths of concrete are significantly influenced by fiber length. Higher fiber content favors short fibers for better compressive strength, while long fibers offer superior flexural strength despite lower compressive strength compared to shorter PP fibers [7][18].

The research employed two distinct fiber types: Hook-Ended Steel Fiber (HKSF-30mm) and Polypropylene Fiber (PP), as depicted in Fig. 1. The steel fiber employed features a Hook-Ended shape, a melting point of 2800C, and length to diameter with an aspect ratio of 53. The polypropylene fiber being used is in a macroscopic form, possessing a melting point of 1800°C, with a diameter of 1.5 mm and a length of 50 mm. Table 1 lists the mechanical properties of various fibers provided by manufacturers [19][20].

(a) (b) (c)

Figure 1: Fiber's Detail (a) Types of fibers (b) Macro polypropylene fibers (c) Hook-Ended steel fibers

Table 1: Fiber's properties [19][20]

Sr. No	Fiber type	Length (mm)	Tensile Strength (MPa)	Elastic Coefficient	Melting temperature (ºC)	ASTM
01	HKSF	30	2850	200 GPa	-	A820
02	Macro PPF	50	500	5000 MPa	180	-

3 EXPERIMENTAL PROGRAM

3.1 Mix Design

A comprehensive experimental program comprises 36 combinations in total. Among these, one functions as a control batch, while the remaining 35 involve varied HFRC mixtures. The mixtures consist of PPF ranging from 0.2% to 1% of the cement's mass, with an increment of 0.2%, along with steel fibers at concentrations of 0.25%, 0.5%, 0.75%, 1%, 1.5%, 2% to 3% of cement's mass. Furthermore, the 35 composite HFRC mixture concretes are classified into five groups (1.1, 1.2, 1.3, 1.4 and 1.5). Each group has seven different HFRC mixture combinations. The American Concrete Institute (ACI) mix design method is used to calculate the mix design. this design, the targeted compressive strength is achieved through a concrete mix ratio of 1:2.5:3.5, accompanied by a water-cement ratio of 0.55. The concrete mix includes a water content of 113 kg/m3 and a cement content of around 205 kg/m3 within a one-cubic-meter volume. The values of the slump have been observed to range between 78 and 88 mm at this water-cement ratio. To enhance workability without segregation and bleeding in fiber mixes, SP was incorporated at a weight proportion of 1% relative to the cement. Table 2 presents the concrete mixture proportions for each cubic meter concrete.

Table 2: Mixture design proportion

Group Designation	Steel fibers (cement's mass percentage)	Polypropylene (cement's mass percentage)	W/C	Water (Kg/m^3)	Cement (Kg/m^3)	Fine aggregate (Kg/m^3)	Coarse aggregate (Kg/m^3)	SP (Kg/m^3)
Control	None	None	0.55	113	205	603	763	2
01 (5 Combination)	0.25, 0.5, 0.75, 1.0, 1.5, 2, & 3	0.2	-------	------	-------	-------	-------	-------
02 (5 Combination)	----------------	0.4	-------	-------	-------	-------	-------	-------
03 (5 Combination)	----------------	0.6	-------	-------	-------	-------	-------	-------
04 (5 Combination)	----------------	0.8	-------	-------	-------	-------	-------	-------
05 (5 Combination)	----------------	1.0	-------	-------	-------	-------	-------	-------

Note = The dotted line (-----) displays the continuity of similar data.

3.2 Specimen Preparation and Testing

A total of 108 specimens were prepared, each having dimensions of 150mm and 300mm in diameter and height respectively. Among these, 3 specimens were designated as control specimens, while the remaining 105 were categorized as HFRC samples.

To prepare both Polymer Cement Concrete (PCC) and various Hybrid Fiber-Reinforced Concrete (HFRC) formulations, the initial step involved dry mixing of coarse and fine aggregates. Subsequently, a combination of cement and fibers was introduced along with 10% of the total water content. In the next phase, the water was added and thoroughly mixed, constituting 80% of the mixture. Following this, the remaining 10% of water and 1% of Superplasticizer (SP), based on the weight of the cement, were incorporated into the HFRC mixes to ensure optimal workability. The freshly mixed HFRC was then cast into molds in three layers. After pouring each layer, the molds underwent vibration to eliminate any trapped air. Each specimen was left to stand for 24 hours in the laboratory before demolding. Once demolded, the samples were

identified, marked, and immersed in water at a temperature range of approximately 21–25°C. They were kept submerged until the age tests were carried out at 7 and 28 days.
The HFRC specimen's splitting tensile strength was assessed following ASTM 496/C496 standards. A distinct loading mechanism was employed using a compressive testing machine for the splitting tensile test. A total of 108 specimens underwent axial tension testing utilizing a compression testing machine with a 3000 KN capacity, at loading rates of 0.15Mpa/s.

(a) (b) (c)

Figure 2: (a) Concrete cylinders dimensions (b) Casted samples (c) split tensile testing

4 RESULTS AND DISCUSSION

4.1 Split tensile strength

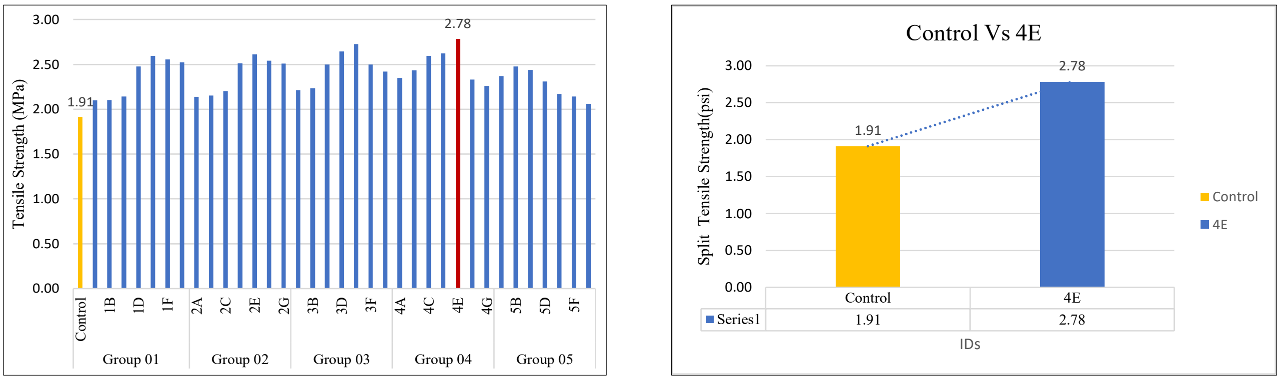
Split Tensile Strength tests were carried out on a total of 108 specimens, comprising 36 different mixes. The results were obtained by averaging the values from three test specimens for each mix, and they are presented in Table 3 for 28 days of age.

Table 3: Test results

Group No.	Sample Identity	Steel fibers	Polypropylene fibers percentage	1st Sample Ultimate load	2nd Sample Ultimate load	3rd Sample Ultimate load	Average Ultimate load	Ultimate Tensile strength $f_{t'}$	$(f_{t'}/f_{control})*100$
Units	-	(Cement's mass %)	(Cement's mass %)	(KN)	(KN)	(KN)	(KN)	(MPa)	-
00	Control	-	-	123	146	136	135	1.91	100
01	1A	0.25	0.2	150	140	155	148.3	2.10	109
	1B	0.50	0.2	145	137	164	148.6	2.10	110
	1C	0.75	0.2	152	167	145	151.3	2.14	112
	1D	1.00	0.2	183	180	162	175	2.48	129
	1E	1.50	0.2	185	170	195	183.3	2.59	135
	1F	2.00	0.2	182	194	166	180	2.56	133
	1G	3.00	0.2	190	185	160	178.3	2.52	132
02	2A	0.25	0.4	151	155	147	151	2.14	111
	2B	0.50	0.4	148	152	157	152.3	2.16	112
	2C	0.75	0.4	163	150	154	155.6	2.20	115
	2D	1.00	0.4	172	178	183	177.6	2.51	131
	2E	1.50	0.4	178	187	189	184.6	2.61	136
	2F	2.00	0.4	172	189	178	179.6	2.54	133
	2G	3.00	0.4	182	175	175	177.3	2.51	131
03	3A	0.25	0.6	157	150	162	156.3	2.21	115
	3B	0.50	0.6	167	148	159	158	2.24	117
	3C	0.75	0.6	177	173	180	176.6	2.50	130
	3D	1.00	0.6	180	200	181	187	2.65	138
	3E	1.50	0.6	204	180	194	192.6	2.73	142

	3F	2.00	0.6	198	164	168	177.6	2.50	130
	3G	3.00	0.6	174	188	151	171	2.42	126
04	4A	0.25	0.8	160	168	170	166	2.35	122
	4B	0.50	0.8	176	168	172	172	2.43	127
	4C	0.75	0.8	183	199	178	183.3	2.59	135
	4D	1.00	0.8	202	173	181	185.3	2.62	137
	4E	1.50	0.8	205	195	190	196.6	2.78	145
	4F	2.00	0.8	155	178	161	164.6	2.33	121
	4G	3.00	0.8	147	159	173	159.6	2.26	118
06	5A	0.25	1.0	178	176	149	167.6	2.37	124
	5B	0.50	1.0	179	182	164	175	2.48	129
	5C	0.75	1.0	171	164	182	172.3	2.44	127
	5D	1.00	1.0	173	162	155	163	2.31	120
	5E	1.50	1.0	158	163	139	153.3	2.17	113
	5F	2.00	1.0	147	152	155	151.3	2.14	112
	5G	3.00	1.0	153	138	146	145.6	2.06	107

Synthetic polypropylene fibers enhance Hybrid Fiber-Reinforced Concrete (HFRC) performance by reducing plastic shrinkage and improving ductility but have limited impact on tensile strength. All 5 groups with 7 combinations each show a consistent trend in tensile strength, indicating that varying polypropylene fiber percentage does not significantly enhance strength because of the low modulus of elasticity. However, increasing steel fiber percentage notably improves tensile strength because of the steel fibers' high modulus of elasticity. Adding more fiber beyond a specific limit reduces HFRC strength. Overall, fiber hybridization enhances tensile strength response, especially within peak ranges. Combination 4E (1.5% hooked-ended steel fibers and 0.8% synthetic polypropylene fibers) shows the highest observed tensile strength of 2.78 MPa, a 45% increase over control specimens. In Group 5, excessive fiber concentration leads to a decline in HFRC tensile strength due to increased air voids and clumping, compromising mechanical performance.



(a) (b)

Figure 3: (a) Tensile Strength bar charts of specimens (b) Comparison of control specimen with optimal percentage specimen

5 CONCLUSIONS AND RECOMMENDATIONS

The influence of increasing PPF content alongside steel fibers on tensile strength is significant. The overall response of Hybrid Fibers Reinforced concrete is enhanced by the incorporation of hybrid fibers, which include steel and polypropylene. The optimal percentage of steel and polypropylene fibers for achieving a maximum tensile strength of 2.78 MPa was achieved at 1.5% and 0.8% of the cement respectively. A substantial 45% enhancement is observed compared to control specimens. Excessive fibers addition resulted in clumps, poor dispersion, increased trapped air, and impaired mechanical performance.

REFERENCES

[1] B. L. Iverson and P. B. Dervan, “No 主観的健康感を中心とした在宅高齢者における 健康関連指標に関する共分散構造分析Title,” pp. 7823–7830.

[2] L. Vandewalle, “Postcracking behaviour of hybrid steel fiber reinforced concrete,” *Proc. 6th Int. Conf. Fract. Mech. Concr. Concr. Struct.*, vol. 3, pp. 1367–1375, 2007.

[3] W. Yao, J. Li, and K. Wu, “Mechanical properties of hybrid fiber-reinforced concrete at low fiber volume fraction,” *Cem. Concr. Res.*, vol. 33, pp. 27–30, Jan. 2003, doi: 10.1016/S0008-8846(02)00913-4.

[4] A. Brandt, *Cement-Based Composites: Materials, Mechanical Properties and Performance*. 2009. doi: 10.1201/9781482265866.

[5] M. Halvaei, M. Jamshidi, and M. Latifi, “Investigation on pullout behavior of different polymeric fibers from fine aggregates concrete,” *J. Ind. Text.*, vol. 45, no. 5, pp. 995–1008, Sep. 2014, doi: 10.1177/1528083714551437.

[6] M. Halvaei, M. Jamshidi, H. R. Pakravan, and M. Latifi, “Interfacial bonding of fine aggregate concrete to low modulus fibers,” *Constr. Build. Mater.*, vol. 95, pp. 117–123, 2015, doi: https://doi.org/10.1016/j.conbuildmat.2015.07.024.

[7] G. Laxmi, S. Patil, N. Hossiney, and H. K. Thejas, “Effect of hooked end steel fibers on strength and durability properties of ambient cured geopolymer concrete,” *Case Stud. Constr. Mater.*, vol. 18, no. May, p. e02122, 2023, doi: 10.1016/j.cscm.2023.e02122.

[8] H. Hosseinzadeh, A. Masoud Salehi, M. Mehraein, and G. Asadollahfardi, “The effects of steel, polypropylene, and high-performance macro polypropylene fibers on mechanical properties and durability of high-strength concrete,” *Constr. Build. Mater.*, vol. 386, p. 131589, 2023, doi: https://doi.org/10.1016/j.conbuildmat.2023.131589.

[9] R. Olivito and F. Zuccarello, “An experimental study on the tensile strength of steel fiber reinforced concrete,” *Compos. Part B-engineering - Compos PART B-ENG*, vol. 41, pp. 246–255, Apr. 2010, doi: 10.1016/j.compositesb.2009.12.003.

[10] A. Chajec and Ł. Sadowski, “The Effect of Steel and Polypropylene Fibers on the Properties of Horizontally Formed Concrete.,” *Mater. (Basel, Switzerland)*, vol. 13, no. 24, Dec. 2020, doi: 10.3390/ma13245827.

[11] N. Banthia and S. M. Soleimani, “Flexural response of hybrid fiber-reinforced cementitious composites,” *ACI Mater. J.*, vol. 102, pp. 382–389, Nov. 2005.

[12] P. P. Rossi, P. Acker, and Y. Malier, “Effect of steel fibres at two different stages: The material and the structure,” *Mater. Struct.*, vol. 20, pp. 436–439, 1987, [Online]. Available: https://api.semanticscholar.org/CorpusID:137308227

[13] B. Lei, W. Li, H. Liu, Z. Tang, and V. W. Y. Tam, “Synergistic Effects of Polypropylene and Glass Fiber on Mechanical Properties and Durability of Recycled Aggregate Concrete,” *Int. J. Concr. Struct. Mater.*, vol. 14, no. 1, 2020, doi: 10.1186/s40069-020-00411-2.

[14] L. Xu, L. Huang, Y. Chi, and G. Mei, “Tensile Behavior of Steel-Polypropylene Hybrid Fiber- Reinforced Concrete,” no. April 2019, 2016, doi: 10.14359/51688641.

[15] S. Govindasami, S. palayam balasundaram, and R. Harish, “Strength Assessment of Polypropylene Fibre Reinforced Concrete (PPFRC),” *Int. J. Eng. Technol.*, vol. 7, pp. 436–438, Sep. 2018, doi: 10.14419/ijet.v7i3.34.19345.

[16] G. Yildirim, M. Şahmaran, and Ö. Anil, “Engineered cementitious composites-based concrete,” in *Eco-efficient Repair and Rehabilitation of Concrete Infrastructures*, 2018, pp. 387–427. doi: 10.1016/B978-0-08-102181-1.00015-0.

[17] X. Shi, P. Park, Y. Rew, K. Huang, and C. Sim, “Constitutive behaviors of steel fiber reinforced concrete under uniaxial compression and tension,” *Constr. Build. Mater.*, vol. 233, p. 117316, 2020, doi: 10.1016/j.conbuildmat.2019.117316.

[18] I. A. Memon, A. A. Jhatial, S. Sohu, M. T. Lakhiar, and Z. H. Khaskheli, “Influence of Fibre Length on the Behaviour of Polypropylene Fibre Reinforced Cement Concrete,” *Civ. Eng. J.*, vol. 4, no. 9, pp. 2124–2131, 2018, doi: 10.28991/cej-03091144.

[19] “End Hooked Uhpc Micro Steel Fiber.” https://www.gzdymf.com/Product/C-GSF-Micro-Steel-Fiber.html

[20] “Macro Synthetic PP Fiber.” https://leade888.en.made-in-china.com/product/cOatIdDZylVw/China-50mm-PP-Waved-Macro-Synthetic-Fiber-for-Spray-Concrete.html