Experimental Investigation on Mechanical Properties of Hybrid Fiber Reinforced Quaternary Cement Concrete

Ramesh Kanagavel[1], Dr. K.Arunachalam[2]

[1]Department of Civil Engineering, K.L.N. College of Information Technology, Tamil Nadu INDIA

[2]Department of Civil Engineering, Thiagarajar College of Engineering, Tamil Nadu INDIA

Correspondence to:
Ramesh Kanagavel email: ramesh_kanagavel@rediffmail.com

ABSTRACT

Mechanical properties of quaternary blending cement concrete reinforced with hybrid fibers are evaluated in this experimental study. The steel fibers were added at volume fractions of 0.5%, 1%, and 1.5 % and polypropylene fibers were added at 0.25% and 0.5% by weight of cementitious materials in the concrete mix individually and in hybrid form to determine the compressive strength, split tensile strength, flexural strength and impact resistance for all the mixes. The experimental results revealed that fiber addition improves the mechanical properties and also the ductility and energy absorption of the concrete. The results also demonstrate that the hybrid steel – polypropylene fiber reinforced concrete performs better in compressive strength, split tensile strength, flexural strength and impact resistance than mono steel and mono polypropylene fiber reinforced concrete.

Keywords: Quaternary; Hybrid fibers; Compressive strength; Split tensile strength; Flexural strength; Impact resistance

INTRODUCTION

Today, studies focusing on fiber hybridization in multiple blending Portland cement concrete are becoming important due to environmental and structural considerations. Incorporation of multiple blending Supplementary Cementitious Materials (SCMs) in concrete are growing in the construction industry due to economical and environmental benefits, and enhanced concrete properties. Kathirvel et al [1] investigated the optimum percentage of SCMs like Fly Ash (FA), Rice Husk Ash (RHA) and Lime stone Powder (LP) in a quaternary mix, with respect to strength and durability. They concluded that the compressive, split tensile, and flexural strengths increased together with the durability of the concrete in a quaternary blending for cement with 20% FA, 10% LP and 10% RHA. Unreinforced concrete has a low tensile strength and a low strain capacity at fracture [2]. In addition to static loads, many concrete structures are often subjected to short duration dynamic loads such as impact from missiles and projectiles, wind gusts, earthquakes and machine vibrations. Under impact loading, plain concrete fails suddenly and in a brittle manner [3, 4]. To overcome this weakness, fibers are added in concrete and improved mechanical properties are obtained [5, 6]. Addition of fibers enhance compressive, tensile and shear strength, flexural toughness, durability, impact strength, etc., [3,7,8] and reduce the drying shrinkage [9]. The brittleness of concrete increases with addition of silica fume to concrete, however, incorporating silica fume with steel fibers [10, 11] and silica fume with polypropylene fibers [12] in concrete increase the energy absorption capacity of concrete. Fiber Reinforced Concrete (FRC) with mono fiber may improve the properties of composites to a limited level [13]. The hybrid fiber systems enhanced the overall performance of the composite, exceeding the sum of the individual performance [14]. It is well established that the incorporation of different kinds of hybrid fibers in concrete improve the engineering performance of concrete and give better mechanical properties [15-21].

From previously published results, it has been found that there has not been enough research on hybrid fiber reinforced concrete with quaternary blending cement concrete. Therefore, an attempt has been made to study the effects of different percentages of steel-polypropylene hybrid fibers on the strength and impact resistance of quaternary mix blending cement concrete without chemical admixture. The effect of mono steel fiber and mono polypropylene fiber in quaternary blending cement concrete are also investigated and reported.

EXPERIMENTAL PROGRAM

Materials Properties

Ordinary Portland Cement (OPC) 53-grade with a specify gravity of 3.11, coarse aggregate of hard broken granite stone passing through 12.5 mm and retained on 4.75 mm sieve with specify gravity of 2.70, fine aggregate having a specific gravity of 2.60 and ordinary potable water were used. FA was collected from the Thermal Power Station at Tuticorin, Tamil Nadu, India. The RHA, grey in color with specific gravity 2.3 and the locally available LP with specific gravity of 2.80 were used. The chemical composition of FA, RHA and LP are given in *Table I*. The low carbon hooked end steel fibers and fibrillated polypropylene fibers were used in this investigation. The steel fiber had a length of 35 mm, diameter of 0.45 mm, aspect ratio of 78, specific gravity of 7.86 and tensile strength ranging between 800 and 1000 MPa. The fibrillated poly-propylene fiber (PP) had a length of 20 mm, diameter of 0.04mm, specific gravity of 0.91 and tensile strength ranging between 350 and 450 MPa.

TABLE I. Chemical composition of FA, RHA and LP.

Composition (%)	FA	RHA	LP
Chemical composition			
SiO_2	60.24	87.02	6.83
$Al_2O_3+Fe_2O_3$	35.34	-	-
Fe_2O_3	7.84	0.64	4.51
Al_2O_3	27.50	1.12	4.14
CaO	0.59	0.64	55.71
MgO	0.85	0.63	5.12
SO_3	0.03	0.58	0.20
Na_2O	0.00	0.14	0.18
K_2O	0.02	0.19	0.04
S	0.00	-	-
LOI	0.72	7.76	22.00

Mixing Proportion

The plain concrete mix proportion for M30 concrete was designed to comply with IS 10262-2009 [22]. The mix proportion was 1:1.61:2.25 with a w/c ratio of 0.48. The quaternary mix was treated as the control mix in which OPC was partially replaced with 20% FA, 10% RHA and 10% LP by weight of cement based on the earlier investigation done by Kathirvel et al [1]. The mix proportion including cementitious materials is shown in *Table II*. This mix proportion was kept constant for all twelve mixtures. The steel fibers were added in 0.5%, 1%, and 1.5 % by volume of concrete and PP fibers were added in 0.25% and 0.5% by weight of cementitious materials. The fibers were added with different proportions in the concrete mix as shown in *Table III*.

Mixing Procedures

Initially, the coarse and fine aggregates were mixed in the concrete mixer for one minute. The cementitious materials (cement + fly ash + RHA + LP) were added and the dry mixing was done for about two minutes. Then water was added and mixing continued for another 5 minutes. Finally, the specified amount of fibers were added to the mixtures and mixed for five minutes to achieve a uniform distribution.

TABLE II. Mix proportion including cementitious materials.

Material	Proportion	Quantity kg/ m^3
Cement	0.6	260.72
FA	0.2	86.91
RHA	0.1	43.45
LP	0.1	43.45
Fine aggregate	1.61	698.90
Coarse aggregate	2.25	977.92
Water	0.48	208.575

TABLE III. Fiber ratios in mixes.

Mix Designation	Steel fiber ratio V_f(%)	PP fiber ratio W_f(%)
C	0.00	0.00
S1	0.50	0.00
S2	1.00	0.00
S3	1.50	0.00
P1	0.00	0.25
P2	0.00	0.50
S1P1	0.50	0.25
S2P1	1.00	0.25
S3P1	1.50	0.25
S1P2	0.50	0.50
S2P2	1.00	0.50
S3P2	1.50	0.50

V_f – volume fraction, W_f – weight fraction

Casting and Testing

The fresh concrete was cast in a cube (150mm x150mm x 150mm), cylinder (150 mm diameter x 300 mm length), and beam (100mm x 100mm x 500 mm) moulds and compacted with a table vibrator for compressive, splitting tensile, and flexural strength tests respectively. Cylindrical (150 mm diameter x 64 mm thick) disc specimens were used for impact tests. The specimens were demoulded after 24 hours and cured in water until tested.

Testing Methodology

The Vee Bee consistometer test was used to measure the workability of the concrete mixture. The Vee Bee consistometer test was conducted as per IS 1199-1959 (R1999) [23]. A compressive strength test was conducted on cube specimens and a flexure strength test was conducted on beam specimens with two point loading as per IS 516-1959 (R1999) [24]. A split tensile test was carried out on cylinder specimens per IS 5816-1999 [25]. The impact resistance of the concrete specimen was determined by the ACI Committee 544 drop weight impact test [26]. Three specimens were tested for compressive, split tensile, and flexural strength, and five specimens for impact resistance strength and the average value was calculated. All the specimens were tested at the age of 28 days. The results were compared with the control specimen that contained cement replacement materials without fibers. The impact test specimen cylindrical discs (150mm diameter x 64 mm thick) were cut from 150 mm diameter x 300 mm length cylinder specimens and prepared. The impact specimen was placed on a base plate with four positioning lugs of the impact testing equipment. The steel ball with 63.5 mm diameter was placed at the center of the top surface of the concrete disc specimen. The drop hammer weight of 4.54 kg (44.54 N) was then placed vertically on the steel ball. The hammer was dropped repeatedly on the steel ball from a height of 457 mm. The schematic diagram of the impact strength test set up is shown in *Figure 1*. The number of blows required to cause the first visible crack (N1) and ultimate failure (N2) was recorded as the first crack strength and the ultimate failure strength. The impact energy absorption capacity of the concrete specimen was calculated [27, 28] by the following Eq. (1).

$$E_{imp} = Nmgh \text{ Joule} \quad (1)$$

where E_{imp} = impact energy in Joule(J); m=mass of drop hammer in kg; g=9.81m/s^2; h=releasing height of drop hammer in m ; N=number of blows.

RESULTS AND DISCUSSION

The workability, compressive, split tensile, flexural, and the impact test results are presented in *Table IV* and graphically shown in *Figures 2* to *4*. The increase in percentage of compressive, split tensile, and flexural strength over the control concrete at 28 days are shown in *Table V.*

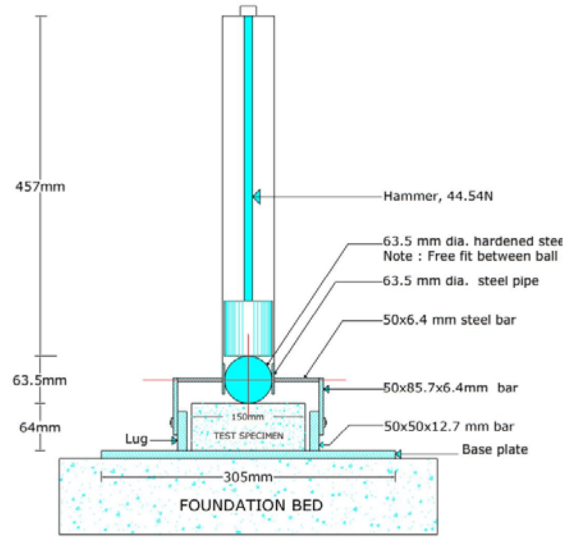


FIGURE 1. Schematic Diagram of the Drop Weight Method Test Setup.

Workability

Table IV shows the Vee Bee time results for the mono and hybrid fiber reinforced concrete mixes. The Vee Bee test gave a more accurate indication of the workability of the FRC than the standard slump test and compacting factor test [29]. Studies have established that a mixture with relatively low slump can have good consolidation properties under vibration [2]. Even at very low slump, FRC mixtures respond well to vibration [26]. It was found that the addition of steel and polypropylene fibers in fresh concrete increased the Vee Bee time. Also, when the fiber content was increased, the Vee Bee time further increased, decreasing the workability of the concrete. In Steel Polypropylene Hybrid Fiber Reinforced Concrete (SPHFRC), the Vee Bee time ranged between 10 seconds and 61 seconds. The Vee Bee time increased by 6, 16, and 39 seconds with the addition of steel fiber at 0.5%, 1%, and 1.5% by volume respectively and for polypropylene fibers at 0.25% and 0.5% by weight, the Vee Bee time increased by 4 and 7 seconds respectively. These results are in accordance with previous results. Tayfun Uygunoglu reported [29] that the addition of steel fibers increased the Vee Bee time ranging between 2 seconds and 70 seconds for a 0-1.3% fiber volume fraction. Similar findings were reported by Ozgur Eren and Khaled Marar [30] with the addition of hooked end steel fibers increasing the Vee Bee time. O.Karahan and C.D. Atis [31] also reported that inclusion of fibrillated polypropylene fiber increased the Vee Bee time.

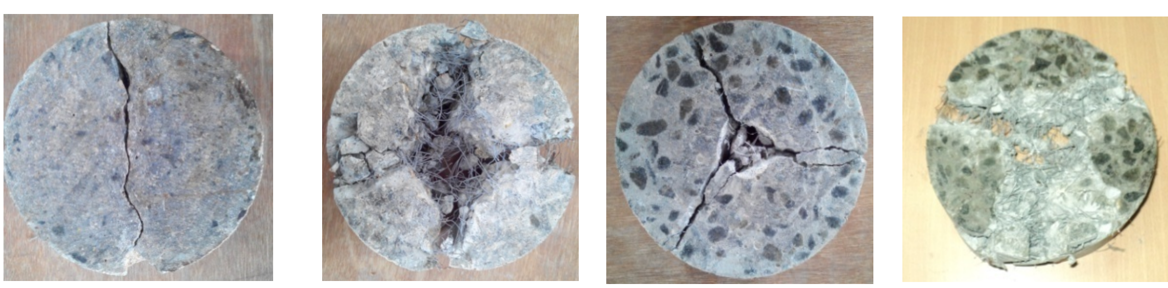
TABLE IV. Results of Workability, Compressive, Split Tensile, Flexural Strength and Impact Resistance.

Mix Designation	Compressive Strength (N/mm^2)	Split Tensile Strength (N/mm^2)	Flexural Strength (N/mm^2)	Vee Bee time in seconds	Impact Resistance				
					Number of blows		Impact Energy (*J*)		Percentage increase in post crack resistance
					First crack (N1)	Failure (N2)	First crack	Failure	
C	37.16	3.6	4.31	3	251	252	5108.8	5129.1	0.4
S1	43.08	4.55	5.74	6	763	893	15529.8	18175.8	17
S2	47.67	5.63	9.36	16	993	1240	20211.1	25238.5	24.9
S3	46.86	7.58	12.65	39	1191	1870	24241.1	38061.2	57
P1	40.33	3.72	5.3	4	668	694	13596.2	14125.4	3.9
P2	38.79	3.85	5.46	7	730	780	14858.1	15875.8	6.8
S1P1	45.42	4.97	6.84	10	910	1085	18521.8	22083.6	19.2
S2P1	46.27	5.48	8.74	19	1097	1496	22327.9	30449	36.4
S3P1	45.02	6.97	11.84	43	1264	2056	25726.9	41847	62.7
S1P2	46.53	4.65	7.48	14	967	1173	19681.9	23874.8	21.3
S2P2	44.61	5.28	8.42	25	1178	1621	23976.5	32993.2	37.6
S3P2	44.49	6.08	11.34	61	1396	2301	28413.6	46833.6	64.8

V_f % volume fraction, W_t% weight basis

TABLE V. Percentage increase in Compressive, Split tensile and Flexural Strength.

Mix Design ation	Percentage increase in compressive strength %	Percentage increase in split tensile strength %	Percentage increase in flexural strength %
C	0.00	0	0
S1	15.93	26.39	33.18
S2	28.28	56.39	117.17
S3	26.10	110.56	193.50
P1	8.53	3.33	22.97
P2	4.39	6.94	26.68
S1P1	22.23	38.06	58.70
S2P1	24.52	52.22	102.78
S3P1	21.15	93.61	174.71
S1P2	25.22	29.17	73.55
S2P2	20.05	46.67	95.36
S3P2	19.73	68.89	163.11



(a) (b) (c) (d)

FIGURE 7. Failure pattern of the concrete specimen (a) Control specimen (b) SFRC (c) PFRC (d) SPHFRC.

Compressive Strength

The compressive strength test results are presented in *Table IV* and *Figure 2*. From the test results, it was found that the compressive strength of Steel Fiber Reinforced Concrete (SFRC), Polypropylene Fiber Reinforced Concrete (PFRC), and SPHFRC are found to be higher than the control mix. Compared to the control concrete, compressive strength improvement in SFRC increased by 16%, 28%, and 26% for concrete mixes having 0.5%, 1%, and 1.5% volume fraction of steel fibers respectively and the maximum increase in compressive strength was 28% for 1% volume fraction. The compressive strength in PFRC increased from about 4% to 9% and in SPHFRC from about 20% to 25%. The significant positive synergy was observed in the hybrid mix S1P1 and S1P2 when compared to mix S1. The strength improvement is up to about 22% in the hybrid mix S1P1 and 25% in S1P2 mix whereas 16% in the S1 mix over the control concrete. These results are in accordance with previous results. Campione et al [32] reported that compressive strength increased up to 30% when steel fibers were added into light weight expanded clay aggregate concrete. Y. Mohammadi et al [33] reported that the increase in compressive strength of up to 26% in SFRC is due to addition of fibers in concrete. M. Hsie et al [17] reported that increase in compressive strength ranged from 4.65% to 13.24% due to addition of coarse monofilament polypropylene fibers to the concrete. Kim Hung Mo et al [28] reported that the highest enhancement of compressive strength, 34%, was found when hooked steel and fibrillated polypropylene fiber were added into oil palm shell concrete.

FIGURE 2. Compressive strength at 28 days.

However, the strength reduction was observed in hybrid mixes other than the mono steel mix at 1% and 1.5% volume fraction. When the fiber percentage is increased, effect of balling will come into play which will lead to poor workability. At the higher percentage of hybridization, higher amount of fibers induces the higher porosity in the matrix and also interferes with the cohesiveness of the concrete matrix leading to the balling effect and hence the compressive strength is reduced.

Split Tensile Strength

The split tensile strength test results are presented in *Table IV* and *Figure 3*. The inclusion of fibers in the concrete mix increased the split tensile strength of the SFRC, PFRC, and SPHFRC mix than the control concrete. The improvement of the split tensile strength in SFRC was observed from about 26% to 111% and for PFRC 3% to 7% and also in SPHFRC 29% to 94% over the control concrete at 28 days. Due to fiber hybridization, the significant positive synergy was observed in mix S1P1 and S1P2 when compared with mix S1 at a 0.5% steel volume fraction. The strength improvement was up to about 38% in the hybrid mix S1P1and 29% in the S1P2 mix whereas 26% in S1 mix over the control concrete. These results are in accordance with previous results. M.Hsie et al [17] observed that addition of monofilament polypropylene fiber increased the split tensile strength by up to 8.42% over the control concrete. A.Sivakumar and M.Santhanam [15] observed that the split tensile strength increased up to 26.83% due to addition of 0.5% volume fraction of steel fiber over the control concrete. The reason for strength improvement could be a denser matrix produced by the presence of SCMs and better bond achieved between fibers and composites. The bond strength was increased due to interfacial adhesion and mechanical anchoring and interlocking [14]. Hooked end steel fibers provide good anchorage. The complex fiber geometry of cross-linked network fibrillated polypropylene fiber improves the bond with the matrix by providing an interlocking effect. Due to the low specific gravity of polypropylene, a larger number of fibers will be available at the critical section. When these fibers combine with the high stiffness of steel fibers, the split tensile strength was increased [15]. Thus, the split tensile strength is increased by the combination of high modulus steel fibers with low modulus polypropylene fibers. The split tensile strength reduction was observed in hybrid mixes S2P1, S2P2, S3P1, and S3P2 more so than mix S2 and S3 at 1% and 1.5% volume fraction. Due to the higher percentage of hybridization, higher amount of fibers induce higher porosity and a weak interface zone is formed in the matrix because of the balling effect and hence the split tensile strength is reduced. Hybridization was less effective at higher fiber dosage rates [34].

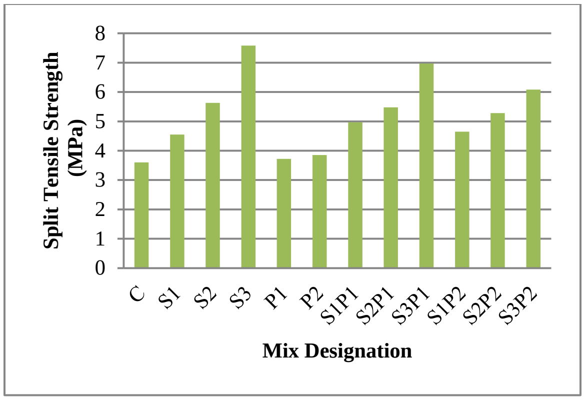


FIGURE 3. Split tensile strength at 28 days.

Flexural Strength

The flexural strength test results for various mixes are presented in *Table IV* and *Figure 4*. The flexural strength was increased in SFRC, PFRC, and SPHFRC mix over the control concrete. The flexural strength of SFRC increases from about 33% to 194%, 23% to 27% for PFRC, and 59% to 175% for SPHFRC over the control concrete at 28 days. In mix S1, strength was increased by 33% over the control concrete at 28 days. However, when polypropylene was added to this mono steel mix, the strength was increased by 59% in mix S1P1 and 74% in mix S1P2 over the control concrete at 28 days. This was due to a significant positive synergy effect due to fiber hybridization. The flexural strength test showed that beams without fibers had very little ductility and once the maximum tensile stress was reached, the beams failed suddenly without warning in a brittle manner after the occurrence of a first crack. The failure characteristics were completely changed as a result of the addition of steel fibers. After the occurrence of the initial crack, the specimen did not fail suddenly. The randomly oriented fibers crossing the cracked section resisted the propagation of cracks and separation of the section. This caused an increase in the load carrying capacity beyond first cracking. Similar findings were reported by Nicolas Ali Libre et al [35] in which flexural strength was increased up to about 200% when steel fibers were added into light weight natural pumice aggregate concrete. W.Yao et al [21] also observed that inclusion of hooked end steel fibers increased the modulus of rupture up to 24.55% over the control concrete due to addition of 0.5% volume fraction of steel fiber. The reason for this strength improvement is the same as in the split tensile strength. The flexural strength was reduced in the hybrid mixes S2P1, S2P2 and S3P1, S3P2 than the mono mix S2 and S3 at 1% and 1.5% volume fraction respectively. This reduction was due to higher amount of fibers inducing the higher porosity and weak interface zone formed in the matrix.

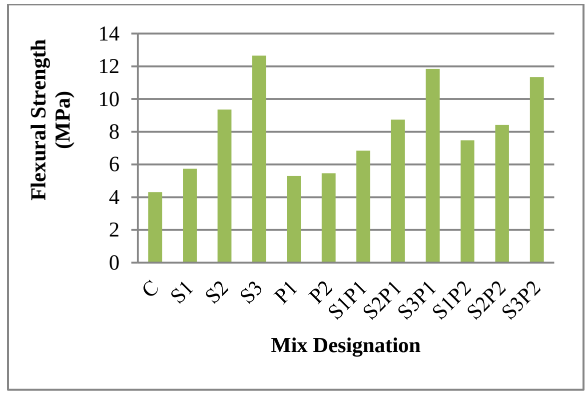


FIGURE 4. Flexural strength at 28 days.

Impact Test

Table IV exhibits the impact resistance of concrete mixes. *Figure 5* and *6* show the number of blows required to cause first crack (N1), ultimate failure (N2), and percentage increase in post crack resistance for all mixes. The percentage increase in post crack resistance is negligible in control concrete specimens. For control concrete, N1 and N2 values are almost the same due to brittle failure behavior [10, 18]. The impact resistance of SFRC, PFRC, and SPHFRC increase with increasing fiber content. The post crack resistance of SFRC increases from 17 % to 57% and 3.9 % to 6.8 % for PFRC and 19.2% to 64.8% for SPHFRC over the control concrete at 28 days. In SFRC, the maximum percentage increase in post crack resistance, 57%, was obtained at 1.5% volume fraction. These results are in accordance with previous investigations. M.C.Nataraja et al [l4] reported that the percentage increase in post crack resistance was about 50% in SFRC. Semsi Yazıcı et al [36] reported that among the SFRCs exposed to impact loading effects, the best performances were obtained at 1.5% volume of steel fibers in the concrete. The percentage increase in post crack resistance is higher in all SPHFRC than mono fiber systems. The maximum percentage increase in post crack resistance is 64.8% in SPHFRC mix S3P2. Addition of low modulus polypropylene fibers to the high modulus steel may be the reason for the percentage increase in post crack resistance. Due to fiber hybridization, the significant positive synergy was observed in all SPHFRC mix.

In the SFRC mix, N1 increased from 3.04 to 4.75 times and N2 increased from 3.54 to 7.42 times over the control concrete at 28 days. In the S3 mix, N1 and N2 increase by 4.75 and 7.42 times over the control concrete at 28 days. A similar finding has been reported by H.T. Wang and L.C. Wang [37] that the mean value of the first-crack and failure strength of Steel Fiber Reinforced Lightweight aggregate Concrete (SFLWC) with volume fraction of 1.5% was increased by 4 and 8.5 times compared with Light Weight aggregate Concrete (LWC) at 28 days. In the PFRC mix, N1 increased from 2.66 to 2.91 times and N2 increased from 2.75 to 3.10 times over the control concrete at 28 days. In the SPHFRC mix, N1 increased from 3.63 to 5.56 times and N2 increased from 4.31 to 9.13 times over the control concrete at 28 days. These results reveal that the fiber hybridization enhances the performance against impact of the concrete and also increases the post cracking strength over the mono fiber system. The significant positive synergy was observed in all the hybrid mixes when compared to mono SFRC. The impact energy in first crack and ultimate failure increased by 19.27% and 21.50% in the S1P1 mix, whereas 26.74% and 31.35% in the S1P2 mix over the S1 mix at 28 days. The impact energy in first crack and ultimate failure increased by 10.47% and 20.65% in the S2P1 mix, whereas 18.63% and 30.73% in the S2P2 mix over the S2mix at 28 days. The impact energy in first crack and ultimate failure increased by 6.13% and 9.95% in the S3P1 mix, whereas 17.21% and 23.05% in the S3P2 mix over the S3mix at 28 days.

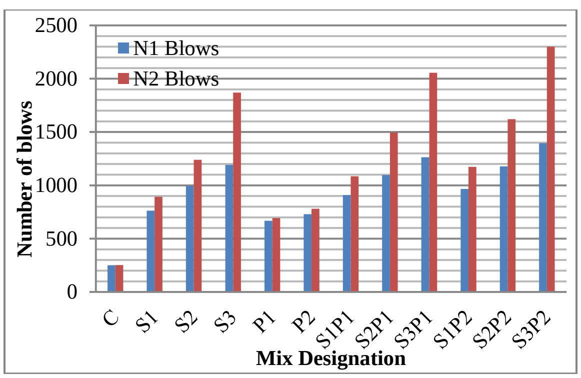


FIGURE 5. Impact resistance at first crack and ultimate failure.

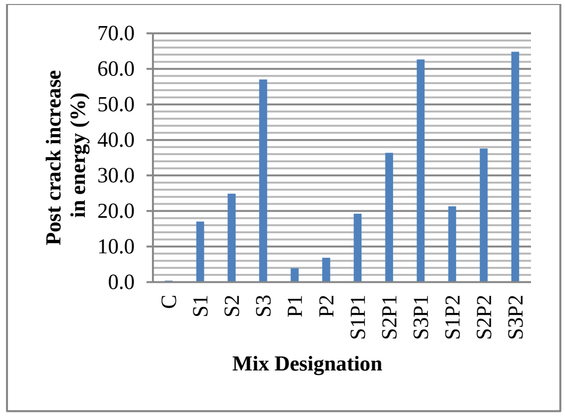


FIGURE 6. Post crack strength Energy for all mixes.

The failure pattern of the control, SFRC, PFRC, and SPHFRC impact specimens are shown in *Figure 7*. The control specimens failed suddenly in a brittle manner and lost structural integrity. The PFRC specimens fractured into two and three pieces with thin cracks. The multiple cracking failure pattern occurred in the SFRC specimens. These failure patterns are in agreement with the results of Tara Rahmani et al [3]. Results of Mahmoud Nili and V. Afroughsabet [10, 12] also support this conclusion. In SPHFRC, the failure pattern was changed from a single large crack to multiple cracks while retaining structural integrity over the control and mono fiber reinforced concrete specimens. Structural integrity is critical for concrete structures when subjected to short duration dynamic loading.

CONCLUSION

Based on the experimental investigations, the following conclusions are drawn.

Addition of steel and polypropylene fibers in fresh concrete increased the Vee Bee time. Workability was drastically decreased both in mono and hybrid fiber systems at higher fiber dosages.

In the SPHFRC mix, the compressive strength was increased by about 20% to 25% and the split tensile strength was increased by about 29% to 94% and also the flexural strength was increased by about 59% to 175% over the control concrete at 28 days. Among all hybrid fiber combinations, mix S1P1 and S1P2 perform better than mono steel and mono polypropylene reinforced concrete.

The inclusion of steel and polypropylene fibers in the concrete mix increased the impact resistance of the concrete. In the SPHFRC mix, N1 increased from 3.63 to 5.56 times and N2 increased from 4.31 to 9.13 times over the control concrete at 28 days. The hybrid mix S3P2 has the highest percentage increase in post crack resistance of 64.8% in 28 days. These results reveal that the fiber hybridization enhanced the performance of the concrete against impact and also increased the post cracking performance over the mono fiber system.

From the test results, a fiber combination of 0.5% steel with 0.25% and 0.5% PP fiber can be taken as the most appropriate hybrid combination for compressive, split tensile, and flexural strength, and a hybrid combination of 1.5% steel with 0.25% and 0.5% PP fiber can be taken as the most appropriate hybrid combination for impact resistance of the concrete.

It can be concluded that incorporation of SCMs in cement concrete blended with hybrid fibers has resulted in advantages due to an improvement in the mechanical properties by the fibers and a beneficial effect of the SCMs on the properties of concrete.

REFERENCES

[1] Kathirvel, P. et al.; Strength and Durability Properties of Quaternary Cement Concrete Made with Fly Ash, Rice Husk Ash and Limestone Powder; *Arabian Journal for Science and Engineering* 2013, 38, 589-598.

[2] ACI 544.1R-96 (Reapproved 2009), Report on Fiber Reinforced Concrete, Reported by *ACI Committee 544*, Farmington Hills,Michigan: *American Concrete Institute*.

[3] Rahmani, T. et al.; Statistical and experimental analysis on the behavior of fiber reinforced concretes subjected to drop weight test; *Construction and Building Materials* 2012, 37, 360–369.

[4] Nataraja, M. C.; Nagaraj, T. S.; Basavaraja, S. B.; Reproportioning of steel fibre reinforced concrete mixes and their impact resistance; *Cement and Concrete Research* 2005, 35, 2350 – 2359.

[5] Khaloo, A. R.; Kim, N.; Mechanical properties of normal to high strength steel fiber reinforced concrete; *Cement, Concrete, and Aggregates, CCAGDP* 1996, 18**,** 92-97.

[6] Bagherzadeh, R. et al.; An Investigation on Adding Polypropylene Fibers to Reinforce Lightweight Cement Composites (LWC); *Journal of Engineered Fibers and Fabrics* 2012, 7, 13-21.

[7] Holschemacher, K.; Mueller, T.; Ribakov, Y.; Effect of steel fibres on mechanical properties of high strength concrete; *Materials and Design* 2010, 31 **,**2604-2615.

[8] Xu, B. W.; Shi, H. S.; Correlations among mechanical properties of steel fiber reinforced concrete; *Construction and Building Materials* 2009, 23, 3468- 3474.

[9] Goel, P.; Kumar,R.; Mathur, R.; An Experimental study on concrete reinforced with Fibrillated Fiber; *Journal of Scientific and Industrial Research* 2012, 71**,** 722- 726.

[10] Nili, M.; Afroughsabet, V.; Combined effect of silica fume and steel fibers on the impact resistance and mechanical properties of concrete; *International Journal of Impact Engineering* 2010, 37**,** 879-886.

[11] Koksal, F. et al.; Combined effect of silica fume and steel fiber on the mechanical properties of high strength concretes; *Construction and Building Materials 2008*, 22**,** 1874–1880.

[12] Nili, M.; Afroughsabet, V.; The effects of silica fume and polypropylene fibers on the impact resistance and mechanical properties of concrete; *Construction and Building Materials 2010*, 24, 927–933.

[13] Sahmaran, M.; Yaman, I. O.; Hybrid fiber reinforced self-compacting concrete with a high- volume coarse fly ash; *Construction and Building Materials* 2007, 21**,** 150-156.

[14] Bentur, A.; Mindess, S.; *Fibre Reinforced Cementitious Composites*; 2nd ed. Taylor & Francis: London and New York, 2007.

[15] Sivakumar, A.; Santhanam, M.; Mechanical properties of high strength concrete reinforced with metallic and non-metallic fibres; *Cement & Concrete Composites* 2007, 29, 603-608.

[16] Lee, G. et al.; Combining polypropylene and nylon fibers to optimize fiber addition for spalling protection of high-strength concrete; *Construction and Building Materials* 2012, 34, 313–320.

[17] Hsie, M.; Tu, C.; Song, P. S.; Mechanical properties of polypropylene hybrid fiber-reinforced concrete; *Materials Science and Engineering A* 2008, 494, 153–157.

[18] Dawood, E. T.; Ramli, M.; Mechanical properties of high strength flowing concrete with hybrid fibers; *Construction andBuilding Materials* 2012, 28**,** 193–200.

[19] Qian, C. X.; Stroeven, P.; Development of hybrid polypropylene-steel fibre-reinforced concrete; *Cement and Concrete Research* 2000, 30**,** 63–69.

[20] Banthia, N.; Sappakittipakorn, M.; Toughness enhancement in steel fiber reinforced concrete through fiber hybridization; *Cement and Concrete Research* 2007, 37**,** 1366–1372.

[21] Yao, W.; Li, J.; Wu, K.; Mechanical properties of hybrid fiber-reinforced concrete at low fiber volume fraction; *Cement and Concrete Research* 2003, 33, 27–30.

[22] IS 10262-2009, Indian Standard Guidelines for concrete mix design proportioning, New Delhi, India: *Bureau of Indian Standards*.

[23] IS 1199-1959, (Reaffirmed 1999), Indian Standard Methods of Sampling and Analysis of Concrete, New Delhi, India: *Bureau of Indian Standards*.

[24] IS 516-1959, (Reaffirmed 1999) Edition 1.2 (1991-07), Indian Standard Methods of Tests for Strength of Concrete, New Delhi, India: *Bureau of Indian Standards*.

[25] IS 5816-1999, Indian Standard Splitting Tensile Strength of Concrete- Method of Test, New Delhi, India: *Bureau of Indian Standards*.

[26] ACI 544.2R-89 (Reapproved 2009), Measurement of Properties of Fiber Reinforced Concrete, Reported by ACI Committee 544, Farmington Hills, Michigan: *American Concrete Institute*.

[27] Alavi Nia, A. et al.; An experimental and numerical study on how steel and polypropylene fibers affect the impact resistance in fiber-reinforced concrete; *International Journal of Impact Engineering* 2012, 46**,** 62-73.

[28] Mo, K. H. et al.; Impact resistance of hybrid fibre-reinforced oil palm shell concrete; *Construction and Building Materials* 2014, 50**,** 499–507.

[29] Uygunoglu, T.; Effect of fiber type and content on bleeding of steel fiber reinforced concrete; *Construction and Building Materials* 2011, 25**,** 766–772.

[30] Eren, O.; Marar, K.; Effect of steel fibers on plastic shrinkage cracking of normal and high strength concretes; *Materials Research* 2010, 13(2), 135-141.

[31] Karahan, O.; Atis, C. D.; The durability properties of polypropylene fiber reinforced fly ash concrete; *Materials and Design* 2011, 32**,** 1044–1049.

[32] Campione, G.; Miraglia, N.; Papia, M.; Mechanical properties of steel fibre reinforced lightweight concrete with pumice stone or expanded clay aggregates; *Materials and Structures/Matériaux et Constructions* 2001, 34**,** 201-210.

[33] Mohammadi, Y.; Singh, S. P.; Kaushik, S. K.; Properties of steel fibrous concrete containing mixed fibres in fresh and hardenedstate; *Construction and Building Materials* 2008, 22**,** 956–965.

[34] Banthia, N. et al.; Fiber synergy in Hybrid Fiber Reinforced (HyFRC) in flexure and direct shear; *Cement & Concrete Composites* 2014, 48**,** 91-97.

[35] Libre, N. A. et al.; Mechanical properties of hybrid fiber reinforced lightweight aggregate concrete made with natural pumice; *Construction and Building Materials* 2011, 25**,** 2458–2464.

[36] Yazıcı, S.; Arel, H. S.; Tabak, V.; The effects of impact loading on the mechanical properties of the SFRCs; *Construction and Building Materials* 2013, 41**,** 68-72.

[37] Wang, H. T.; Wang, L. C.; Experimental study on static and dynamic mechanical properties of steel fiber reinforced lightweight aggregate concrete; *Construction and Building Materials* 2013, 38**,** 1146–1151.

AUTHORS' ADDRESSES

Ramesh Kanagavel
Department of Civil Engineering
K.L.N.College of Information Technology
Tamil Nadu
INDIA

Dr. K.Arunachalam
Department of Civil Engineering
Thiagarajar College of Engineering
Tamil Nadu
INDIA