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Experimental study on mechanical properties of hybrid fiber quaternary concrete with supplementary cementitious materials subjected to extended curing period

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The present study investigated the effect of Supplementary Cementitious Materials (SCMs) on mechanical properties of quaternary blended hybrid fiber cement concrete subjected to longer curing periods. Cement was partially replaced with SCMs like fly ash, rice husk ash and lime stone powder concrete was reinforced with steel, carbon and fibrillated polypropylene fibers in different proportions. Steel fibers were added at volume fraction of 0.5%, 1% and 1.5 % while carbon and fibrillated polypropylene fibers at weight fraction of 0.25% and 0.5% in the concrete mix. Carbon fibers were added in mono form and in hybrid form with steel and polypropylene fibers. Compressive strength, split tensile strength, flexural strength and impact resistance of all the mixes were investigated at 56 and 90 days. The tests results revealed that steel-carbon and steel-carbon-polypropylene hybrid fiber reinforced concrete performed better in compressive, split tensile, flexural strength properties and impact resistance than control and mono carbon fiber reinforced concrete. The results also revealed that substitution of cement with SCMs greatly influenced the mechanical properties of the fiber reinforced concrete at the later ages.

KEYWORDS: Quaternary; steel fiber; carbon fiber; polypropylene fiber; post crack resistance.

Utilization of industrial and agricultural by-products as Supplementary Cementitious Materials (SCMs) in concrete is gaining importance in the construction industry due to economical, 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 strength increased together with the durability of the concrete in a quaternary blending of cement with 20% FA, 10% LP and 10% RHA. Despite the benefit of concrete made by SCMs in the concrete structures, it is not promising when subject to the short duration impact and dynamic loads. Due to its poor tensile characteristics, it fails in brittle manner against such loads. Addition of fibers enhance its compressive, tensile and shear strength, flexural toughness, durability, impact strength etc.[2-4]. Steel, carbon and polypropylene fibers are generally used in concrete[5]. The brittleness of concrete increases with addition of silica fume to concrete; however, incorporating silica fume with steel fibers[6,7] and silica fume with polypropylene fibers[8] in concrete increases the energy absorption capacity of concrete. The combined use of fibers and pozzolan significantly improved the properties of the concrete at later ages[6]. Fibers are more effective in the presence of pozzolans[9]. Inclusion of fibers in cementitious materials reduces the shrinkage cracking leading to increased durability of the materials[10]. Adding one type of fiber to the concrete can improve the composite properties in some degree of level. When the fibers are added as a hybrid having two or more combinations, the hybrid composites exhibit more attractive engineering properties than the addition of single type of fiber in the composites[5]. Combinations of organic and inorganic fibers improve the both tensile and impact properties of cement-based composites[11].

Earlier research studies have established that inclusion of hybrid fibers in concrete enhanced the engineering performance and mechanical properties than mono fiber reinforced concrete[5,12-15]. Even though hybrid fiber reinforced concrete is advantageous, there is a deficiency existing in the transition zone between fibers and paste with a lot of porosity. Substitution of portion of the cement with pozzolanic materials improved the mechanical properties of hybrid fiber reinforced concretes and reduced the porosity in transition zones[16]. The literature studies regarding the use of hybrid fibers in multi blended cementitious materials are limited. As there is limited research on addition of hybrid fibers in quaternary blended cement concrete, they are thus chosen for this study. The objective of this investigation is to determine the mechanical properties of mono carbon fiber, carbon-steel and carbon-steel-polypropylene hybrid fibers in the quaternary blending of FA, RHA and LP cement concrete at 56 and 90 days.

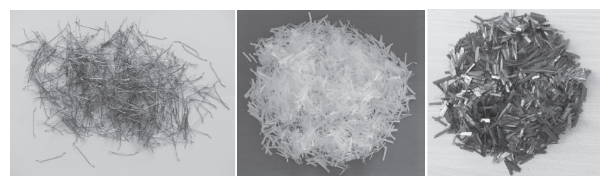
EXPERIMENTAL PROGRAM

Material properties

Ordinary Portland Cement (OPC) 53-grade, FA, RHA and LP were used in this study along with fine and coarse aggregate. The specific gravity of OPC, FA, RHA and LP were 3.11, 2.12, 2.3 and 2.80 respectively. The fine aggregate with specific gravity of 2.60 and hard broken granite stone as coarse aggregate passing through 12.5 mm and retained on 4.75 mm sieve with specific gravity of 2.70 were used. FA was obtained from Tuticorin, Thermal Power Station located in Tamil Nadu, India. Ordinary potable water was used for concrete mix preparation. Chemical composition of FA, RHA and LP are shown in Table 1. Different types of fibers such as low carbon hooked end steel fibers, fibrillated Poly Propylene fibers (PP) and carbon fibers were used in this investigation. The fibers used in this study are shown in Fig. 1. 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 MPa and 1000 MPa. The PP had a length of 20 mm, diameter of 0.04mm, specific gravity of 0.91and tensile strength ranging between 350 MPa and 450 MPa. The length of a carbon fiber was 12 mm, diameter was 11 micron and its carbon content was 95%. The tensile strength and bulk density of a carbon fiber were 4300 MPa, and 554 g/liter respectively.

TABLE 1
CHEMICAL COMPOSITION OF FA, RHA AND LP

Chemical composition (%)	FA	RHA	LP
SiO_2	60.24	87.02	6.83
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
LOI	0.72	7.76	22.00



(a) (b) (c)

Fig. 1 Fibers (a) Steel; (b) fibrillated polypropylene; (c) carbon

Mixing proportion

Proportion of plain concrete mix was arrived at according to IS 10262-2009[17] for M30 grade concrete. The designed mix proportion was 1:1.61:2.25 (Cement: Fine aggregate: Coarse aggregate) with 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 control concrete mix proportion with FA, RHA and LP is shown in Table 2. The carbon fibers were added individually at 0.25% and 0.5% in weight fractions of cementitious materials. When carbon fibers were added in hybrid form with polypropylene fibers, the total weight fraction was maintained at 0.25% and 0.5% weight of cementitious materials. Steel fibers were added at 0.5%, 1% and 1.5 % volume fractions in all carbon, carbon-polypropylene hybrid systems. The different proportion of fibers in the mix is shown in Table 3.

TABLE 2 MIX PROPORTION INCLUDING SCMS		
Material	Proportion	Quantity in 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	208.6

TABLE 3 FIBER COMBINATIONS IN MIXES				
Sl. no.	Mix designation	V_f% of steel fiber	W_f% of polypropylene fiber	W_f% of carbon fiber
1	CC	0	0	0
2	C1	0	0	0.25
3	C2	0	0	0.50
4	S1C1	0.50	0	0.25
5	S1C2	0.50	0	0.50
6	S2C1	1.00	0	0.25
7	S2C2	1.00	0	0.50
8	S3C1	1.50	0	0.25
9	S3C2	1.50	0	0.50
10	S1C0P0	0.50	0.125	0.125
11	S1C1P1	0.50	0.25	0.25
12	S2C0P0	1.00	0.125	0.125
13	S2C1P1	1.00	0.25	0.25
14	S3C0P0	1.50	0.125	0.125
15	S3C1P1	1.50	0.25	0.25
V_f – volume fraction, W_f – weight fraction				

Mixing and casting

The coarse and fine aggregates were mixed initially for 1 minute in the concrete mixer. The cement, FA, RHA and LP were added in the mixer and the dry mixing was done for about 2 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 5 minutes to achieve a uniform distribution. The freshly mixed concrete was cast into the cube of size 150mm ×150mm × 150mm, cylinder of size 150 mm diameter × 300 mm length and prism of size 100mm ×100mm × 500 mm and compacted in table vibrator. Cylindrical specimen of size 150 mm diameter × 64 mm thick discs were used for impact tests. After 24 hour, the specimens were demoulded and cured in water tank until the age of testing. The cube, cylinder and prism specimens were used for compressive, split tensile and flexural strength tests respectively.

Testing methodology

In accordance with IS 1199-1959(R1999)[18], the Vee Bee consistometer test was conducted to measure the workability of fresh concrete mixture. Compressive strength test and flexural strength test with two point loading were carried out as per IS 516-1999[19]. Split tensile strength test was carried out on cylinder specimens as per IS 5816-1999[20]. Impact resistance of the concrete specimen was determined as per ACI Committee Report 544.2R-89 drop weight impact test[21]. The compressive, split tensile and flexural strength tests were carried out on three specimens and impact resistance test was performed on five specimens at the age of 56 and 90 days and the average values were calculated. The test results were compared with the control concrete specimen that contained cement replacement materials without fibers. The impact test specimens (150mm diameter × 64 mm thick cylindrical discs) were cut from 150 mm diameter × 300 mm length cylinder specimen and prepared. The impact specimen was placed on a base plate with four positioning lugs of the impact testing equipment. A hammer with a weight of 4.54 kg was dropped from the height of 457 mm repeatedly on the 63.5 mm diameter steel ball which was placed at the center of the top surface of the concrete disc specimen. The number of blows required to cause the first visible crack (N1) and ultimate failure (N2) were recorded as the first crack strength and the ultimate failure strength. The schematic diagram of the impact resistance test set up is shown in Fig. 2. The impact energy absorption capacity of the concrete specimen was calculated[22,23] by the Eq. (1).

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

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

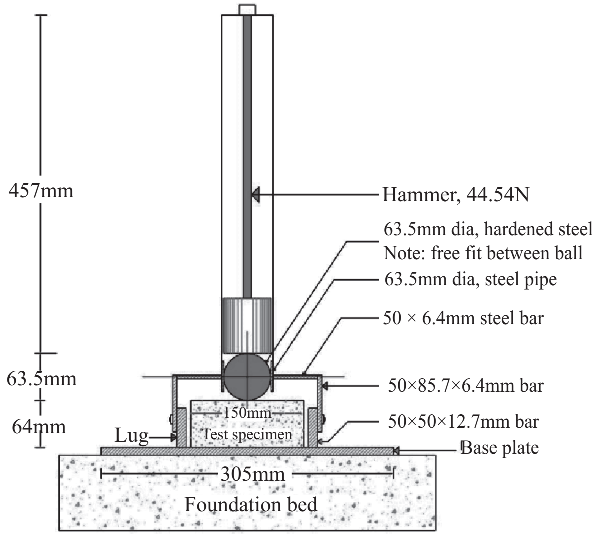


Fig. 2 Schematic diagram of impact resistance test setup

RESULTS AND DISCUSSION

The compressive, split tensile and flexural strength test results at 28 days[24] and at extended curing period are shown in Table 4. The percentage increase in compressive, split tensile and flexural strength of hybrid fiber reinforced concrete is compared with control concrete at the age of 56 and 90 days. The results of all mixtures at 56 and 90 days are also compared with control concrete at 28 days and are shown in Figs. 3-5. The impact resistances of concrete mixes in terms of the number of blows required to cause first crack (N1) and ultimate failure (N2) at 28 days[24] are presented in Table 5 and at 56 and 90 days are shown in Table 6. The percentage increase in post crack resistance for all mixes in 56 and 90 days are shown in Table 6 and Fig. 6.

Compressive strength

The compressive strength test results are given in Table 4. It clearly reveals that the compressive strength of Carbon Fiber Reinforced Concrete (CFRC), Carbon - Steel Hybrid Fiber Reinforced Concrete (CSHFRC), and Carbon-Steel-PP Hybrid Fiber Reinforced Concrete (CSPHFRC) are found to be higher than the control concrete at 56 and 90 days. The strength improvement in CFRC ranges from 20.61 to 30.08% at 56 days and 21.55% to 34.05% at 90 days respectively than control concrete in 56 days and 90 days respectively. The maximum strength improvement is 34.05 % in C1 mix. The strength improvement varies in CSHFRC from 31.65 % to 47.50 % and 35.86 % to 47.55 %, in CSPHFRC from 32.98% to 43.62 % and 36.57% to 43.77 % than control concrete in 56 days and 90 days respectively. The results are also compared between the

TABLE 4
COMPRESSIVE, SPLIT TENSILE AND FLEXURAL STRENGTH AT EXTENDED CURING PERIOD

Sl. No	Mix designation	Compressive strength (N/mm^2)			Split tensile strength (N/mm^2)			Flexural strength (N/mm^2)		
		28 days	56 days	90 days	28 days	56 days	90 days	28 days	56 days	90 days
1	CC	37.16	41.33	44	3.60	3.75	3.82	4.31	4.72	4.94
2	C1	47.96	53.76	58.98	3.98	4.2	4.39	5.50	6.54	7.4
3	C2	44.44	49.85	53.48	4.17	4.42	4.68	5.68	6.72	7.7
4	S1C1	48.53	54.41	59.78	5.00	5.6	5.83	7.20	7.9	8.42
5	S1C2	50.44	56.96	61.78	5.28	5.85	6.18	7.58	8.44	9.18
6	S2C1	54.71	60.96	64.92	6.46	7.45	7.86	9.54	11.16	12.32
7	S2C2	52.98	59.05	63.07	6.84	7.86	8.4	9.90	11.6	12.74
8	S3C1	50.22	56.64	61.47	7.89	8.82	9.39	12.88	14.44	15.65
9	S3C2	49.69	55.88	61.07	8.28	9.04	9.84	13.32	14.86	16.1
10	S1C0P0	49.11	55.53	60.62	5.12	5.73	5.98	7.36	8.1	8.6
11	S1C1P1	52.22	58.19	62.31	5.38	6.05	6.4	7.66	8.54	9.34
12	S2C0P0	53.33	59.36	63.26	6.14	7.19	7.7	9.44	11.02	12.18
13	S2C1P1	52.80	58.81	62.84	6.68	7.6	8.18	9.78	11.4	12.6
14	S3C0P0	49.82	56.10	60.84	7.64	8.56	9.20	12.72	14.32	15.5
15	S3C1P1	48.62	54.96	60.09	7.96	8.91	9.49	13.16	14.72	15.9

two types namely CSPHFRC and CSHFRC systems. Between the hybrid mixes, at 0.5% volume fraction of steel fibers, the significant positive synergy effect is observed only in S1C0P0 and S1C1P1 than CSHFRC mix S1C1 and S1C2. When compared to control concrete at 56 days and 90 days, the maximum strength enhancement in S1C0P0 is at 34.36% at 56 days and 37.77% at 90 days whereas in S1C1P1 is at 40.79 % at 56 days and 41.61 % at 90 days. At 1% and 1.5% volume fraction of steel fibers, CSHFRC mix performs better than CSPHFRC mix. The compressive strength is decreased in mixes S2C0P0 to S3C1P1 than S2C1 to S3C2 mix. Thus, the negative synergy is observed in all other CSPHFRC mixes compared to all CSHFRC mixes at 1% and 1.5% volume fraction of steel fiber. Hybridization is less effective at higher fiber dosage rates[25]. This may be due to balling effect affecting the workability of concrete. The percentage increase in compressive strength at 56 and 90 days than control concrete at 28 days curing are shown in Fig. 3.

The compressive strength of control concrete at 28 days was 37.16 MPa. The percentage increase in compressive strength of control concrete at 90 days than control concrete at 28 days is 18.41%. This result is in accordance with the previous investigation. Ozkan Sengul and Tasdemir[26] reported that the compressive strength improvement between 28 and 90 days was 19% for the concrete with the ternary binder (fly ash + slag). This strength improvement is due to pozzolanic reaction of the materials present in the mix continuing for a longer curing period. When compared to control concrete at 28 days, the strength improvement in CFRC varies from 34.15 % to 44.67 % and 43.92 % to 58.72 % at 56 days and 90 days respectively and the same for CSHFRC 46.42 % to 64.05 %, 60.87 % to 74.70 % and for CSPHFRC 47.90 % to 59.74 %, 61.71 % to 70.24 % at 56 days and 90 days respectively. When compared to C1 and C2 mixes at 28 days, the strength improvement of respective mixes varies from 12.09% to 22.98% and 12.17 % to 20.34% at 56 days and 90 days respectively. Like that, when compared to S1C1, S1C2, S2C1, S2C2, S3C1 and S3C2 mixes at 28 days, the strength improvement of respective mixes varies from 12.12% to 23.18 %, 12.93% to 22.48%, 11.42%to 18.66%, 11.46% to 19.04%, 12.78% to 22.40% and 12.46% to 22.90% at 56 days and 90 days respectively. And also, when compared to S1C0P0, S1C1P1, S2C0P0, S2C1P1, S3C0P0 and S3C1P1 mixes at 28 days, the strength improvement of respective mixes varies from 13.07% to 23.44%, 11.43% to 19.32%, 11.31%to 18.62%,

TABLE 5

RESULTS OF IMPACT RESISTANCE TEST AT 28 DAYS

Sl. No	Mix designation	Impact resistance				Percentage increase in post crack resistance at 28 days
		Number of blows		Impact energy in joule		
		First crack (N1) at 28 days	Failure (N2) at 28 days	First crack at 28 days	Failure at 28 days	
1	CC	251	252	5108.8	5129.1	0.4
2	C1	675	677	13738.7	13779.4	0.3
3	C2	752	754	15305.9	15346.6	0.3
4	S1C1	921	1103	18745.7	22450.0	19.8
5	S1C2	980	1193	19946.5	24281.8	21.7
6	S2C1	1115	1607	22694.3	32708.2	44.1
7	S2C2	1194	1762	24302.2	35863.0	47.6
8	S3C1	1285	2135	26154.4	43454.9	66.1
9	S3C2	1411	2364	28718.9	48115.9	67.5
10	S1C0P0	937	1128	19071.3	22958.9	20.4
11	S1C1P1	997	1219	20292.5	24811.0	22.3
12	S2C0P0	1132	1656	23040.3	33705.5	46.3
13	S2C1P1	1205	1799	24526.1	36616.1	49.3
14	S3C0P0	1323	2210	26927.8	44981.4	67.0
15	S3C1P1	1460	2479	29716.2	50456.6	69.8

11.38% to 19.02%, 12.61 % to 22.12% and 13.04% to 23.59% at 56 days and 90 days respectively. This strength improvement might be due to the pozzolanic materials present in the mix. Similar finding has been reported by Mahmoud and Afroughsabet[6,8]. Due to pozzolanic reaction, the transition zone is densified and interfacial adhesive bond is increased and thus, the bond between the matrix and fibers is enhanced leading to the increase in strength.

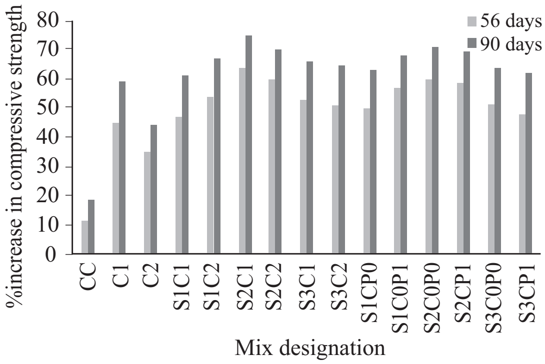


Fig. 3 Percentage increase in compressive strength at 56 and 90 days compared to control concrete at 28 days

Split tensile strength

From the test results shown in the Table 4, the split tensile strength of CFRC, CSHFRC and CSPHFRC increased compared to the control concrete at 56 and 90 days with the addition of fibers. Split tensile strength increases in CFRC from 12% to 17.87% at 56 days and 14.92% to 22.51% at 90 days respectively for concrete specimens having 0.25% and 0.5% carbon fiber than control concrete at 56 days and 90 days respectively. In CSHFRC, the split tensile strength increases from 49.33% to 141.07% and 52.62% to 157.59% and the same for CSPHFRC from 52.80% to 137.60% and 56.54% to 148.43% than control concrete at 56 days and 90 days respectively. The percentage increase in split tensile strength at 56 and 90 days than control concrete at 28 days curing are shown in Fig. 4. S3C2 mix gives the highest split tensile strength. Similar finding has been reported by Wu Yao, et al.[5] as carbon–steel fibers gave the highest split tensile strength. From the test results, the synergy effect is also compared between the two hybrids CSPHFRC and CSHFRC systems. Among the three fibers hybridization, the significant

TABLE 6
RESULTS OF IMPACT RESISTANCE TEST AT 56 AND 90 DAYS

Sl.No.	Mix designation	Impact resistance								Percentage increase in post crack resistance	
		Number of blows				Impact energy in Joule					
		First crack (N1) at 56 days	Failure (N2) at 56 days	First crack (N1) at 90 days	Failure (N2) at 90 days	First crack at 56 days	Failure at 56 days	First crack at 90 days	Failure at 90 days	56 days	90 days
1	CC	347	348	431	432	7062.7	7083.0	8772.4	8792.8	0.29	0.23
2	C1	747	749	815	817	15204.1	15244.8	16588.2	16628.9	0.27	0.25
3	C2	827	829	896	898	16832.4	16873.1	18236.8	18277.5	0.24	0.22
4	S1C1	995	1207	1061	1294	20251.8	24566.8	21595.2	26337.5	21.31	21.96
5	S1C2	1048	1280	1112	1372	21330.6	26052.6	22633.2	27925.1	22.14	23.38
6	S2C1	1230	1798	1457	2156	25034.9	36595.8	29655.2	43882.3	46.18	47.98
7	S2C2	1321	1969	1534	2319	26887.1	40076.2	31222.4	47200.0	49.05	51.17
8	S3C1	1470	2486	1671	2881	29919.8	50599.0	34010.9	58638.7	69.12	72.41
9	S3C2	1604	2730	1821	3205	32647.2	55565.3	37063.9	65233.3	70.20	76.00
10	S1C0P0	1014	1236	1083	1330	20638.5	25157.0	22042.9	27070.3	21.89	22.81
11	S1C1P1	1067	1304	1133	1404	21717.3	26541.1	23060.6	28576.4	22.21	23.92
12	S2C0P0	1263	1862	1495	2216	25706.6	37898.4	30428.6	45103.6	47.43	48.23
13	S2C1P1	1342	2010	1557	2365	27314.5	40910.7	31690.5	48136.2	49.78	51.89
14	S3C0P0	1512	2568	1719	2992	30774.6	52268.0	34987.8	60897.9	69.84	74.05
15	S3C1P1	1662	2857	1888	3358	33827.7	58150.2	38427.6	68347.4	71.90	77.86

positive synergy effect is observed only in S1C0P0 and S1C1P1 than S1C1 and S1C2 at 0.5% steel fibers. The maximum strength increase is up to 52.80% and 56.54% for S1C0P0 and 61.33% and 67.54% for S1C1P1 than control at 56 days and 90 days respectively. The reason for the strength development might be the presence of SCMs, high modulus steel and carbon fiber in the matrix, anchoring effect of hooked end steel fiber, interlocking effect of cross linked network fibrillated polypropylene fibers with the matrix and the availability of more number of polypropylene fibers at the critical section due to its low specific gravity[26]. At 1% and 1.5% volume fraction of steel fibers, the negative synergy is observed in CSPHFRC mixes than CSHFRC mixes. CSHFRC mixes provided higher strength than CSPHFRC mixes. Similar finding has been previously reported by Chen and Liu[15] where the carbon-steel hybrid fiber combination provided the best effect than the carbon-PP- steel fiber combination. At the higher percentage of hybridization, balling effect of fibers occurred and hence the concrete mix is not fully compacted. Due to this, there was a deficiency existing in the transition zone between fibers and paste with a lot of pores and hence the split tensile strength is reduced. This effect is more predominant in CSPHFRC mixes than CSHFRC mixes[24]. Hybridization is less effective at higher fiber dosage rates[25].

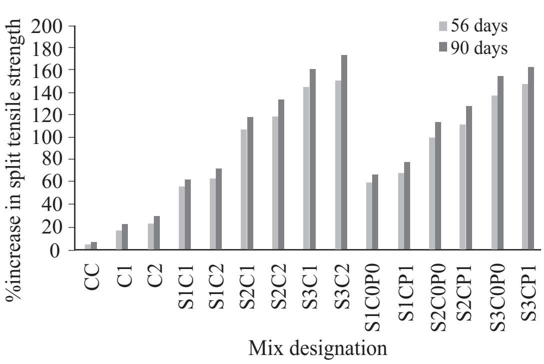


Fig. 4 Percentage increase in split tensile strength at 56 and 90 days compared to control concrete at 28 days

The split tensile strength of control concrete at 28 days was 3.6 MPa. When compared to 28 days split tensile strength of control concrete, the strength increases by 4.17 % and 6.11% at 56 days and 90 days respectively for control concrete. This strength improvement is due to secondary hydration of pozzolanic materials present in the mix at later ages. The strength improvement in CFRC varies from 16.67% to 22.78% and 21.94% to 30% at 56 days and 90 days respectively than control concrete at 28 days. The same for CSHFRC varies from 55.56% to 151.11% and 61.94% to 173.33% and for CSPHFRC varies from 59.17% to 147.50% and 66.11% to 163.61% at 56 days and 90 days respectively than control concrete at 28 days. When compared to C1 and C2 mixes at 28 days, the strength improvement of respective mixes varies from 5.53% to 10.30% and 6% to 12.23% at 56 days and 90 days respectively. Like that, when compared to S1C1, S1C2, S2C1, S2C2, S3C1 and S3C2 mixes at 28 days, the strength improvement of respective mixes varies from 12% to 16.60%, 10.80% to 17.05%, 15.33% to 21.67%, 14.91% to 22.81%, 11.79%to 19.01% and 9.18% to 18.84% at 56 days and 90 days respectively. And also, when compared to S1C0P0, S1C1P1, S2C0P0, S2C1P1, S3C0P0 and S3C1P1mixes at 28 days, the strength improvement of respective mixes varies from 11.91% to 16.80 %, 12.45% to 18.96%, 17.10% to 25.41%, 13.77% to 22.46%, 12.04% to 20.42% and 11.93% to 19.22% at 56 days and 90 days respectively. At longer curing periods, the transition zone is strengthened by pozzolanic reaction of the materials. Due to the densified transition zone, the bond between the matrix and fibers is enhanced thus the strength is increased. Test results show that due to positive synergy effect, CSHFRC system performs well in all volume fractions of steel fibers where as CSPHFRC system performs well only in 0.5% volume fraction of steel fibers. Comparing the percentage increase in compressive strength and split tensile strength, the percentage increase is more in split tensile strength than the compressive strength at all curing ages. The same is found in earlier investigations also indicating that fibers play an important role in enhancing tensile strength than the compressive strength.

Flexural strength

The flexural strength test results for various mixes are shown in Table 4 and the percentage increase in flexural strength at 56 and 90 days compared to control concrete at 28 days are shown in Fig. 5. The test results clearly show that the addition of fibers increases the flexural strength in CFRC, CSHFRC and CSPHFRC mix than control concrete at 56 and 90 days. The flexural strength increases in CFRC from 38.56 to

42.37% at 56 days and 49.80% to 55.87% at 90 days respectively for concrete specimens having 0.25% and 0.5% carbon fiber than control concrete at 56 days and 90 days respectively. In CSHFRC, the flexural strength increases from 67.37% to 214.83% and 70.45% to 225.91% and the same for CSPHFRC from 71.61% to 211.86% and 74.09 to 221.86% than control concrete at 56 days and 90 days respectively. There is a synergy effect existing in the two hybrids CSPHFRC and CSHFRC systems when compared to mono carbon fiber system. The significant positive synergy effect is observed only in S1C0P0 and S1C1P1 than S1C1 and S1C2 at 0.5% steel fibers. The maximum strength increase is up to 71.61% and 74.09% for S1C0P0 and 80.93% and 89.07% for S1C1P1 than control at 56 days and 90 days respectively. The negative synergy is observed in CSPHFRC mixes than CSHFRC mixes at 1% and 1.5% steel fibers. CSHFRC mixes provided the greater strength than the CSPHFRC mixes. The reason for this is same as in the split tensile strength.

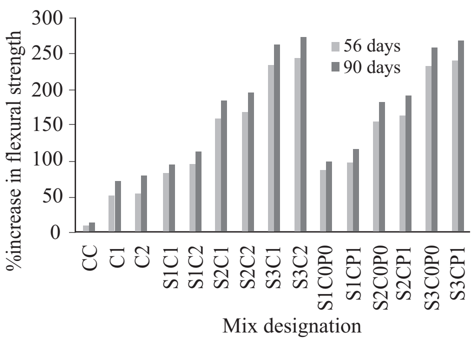


Fig. 5 Percentage increase in flexural strength at 56 and 90 days compared to control concrete at 28 days

The flexural strength of control concrete at 28 days was 4.31 MPa. When compared to 28 days flexural strength of control concrete, the strength increases by 9.51% at 56 days and 14.62% at 90 days respectively for control concrete. The presence of the pozzolanic materials in the mix is responsible for this strength improvement through pozzolanic reaction at later ages. The strength improvement in CFRC, varies from 51.74% to 55.92%, 71.69% to 78.65% and for CSHFRC 83.29% to 244.78%, 95.36% to 273.55% and in CSPHFRC 87.94% to 241.53%, 99.54% to 268.91% at 56 days and 90 days respectively than control concrete at 28 days. When compared to C1 and C2 mixes at 28 days, the strength improvement of respective mixes varies from 18.91% to 34.55% and 18.31% to 35.56% at 56 days and 90 days respectively. Similarly, when compared to S1C1, S1C2, S2C1, S2C2, S3C1 and S3C2 mixes in 28 days, the strength improvement of respective mixes varies from 9.72% to16.94%, 11.35% to 21.11%, 16.98% to 29.14%, 17.17% to 28.69%, 12.11% to 21.51% and 11.56% to 20.87 % at 56 days and 90 days respectively. And also, when compared to S1C0P0, S1C1P1, S2C0P0, S2C1P1, S3C0P0 and S3C1P1mixes at 28 days, the strength improvement of respective mixes varies from 10.05% to 16.85%, 11.49% to 21.93%, 16.74% to 29.03%, 16.56% to 28.83%, 12.58% to 21.86% and 11.85% to 20.82% at 56 days and 90 days respectively. This strength improvement at longer curing periods is due to pozzolanic materials present in the mix as similar to the split tensile strength. When compared to the compressive strength and split tensile strength, the percentage increase in flexural strength is higher.

Impact test

The test results show that the impact resistance of CFRC, CSHFRC and CSPHFRC are higher than control concrete with increasing fiber content at all curing ages. The percentage increase in post crack resistance for all mixes at 56 and 90 days are shown in Fig. 6. The percentage increase in post crack resistance is negligible for control concrete and CFRC specimens. The same for CSHFRC are 21.3% to 70.2% and 22% to 76% and in CSPHFRC are 21.9% to 71.9%, 22.8% to 77.9% at 56 days and 90 days respectively. The percentage increase in post crack resistance is higher in all CSHFRC and CSPHFRC than mono fiber system. The maximum percentage increase in post crack resistance is 71.9% and 77.86% in S3C1P1at 56 and 90 days respectively. The percentage increase in post crack resistance is higher in all CSPHFRC than CSHFRC and mono fiber system. Addition of low modulus polypropylene fibers to the high modulus steel and carbon fiber may also be the reason for the percentage increase in post crack resistance. When polypropylene and carbon fibers (micro fibers) are mixed with steel fibers (macro fibers) either individually or combinedly, they play a better role in increasing the impact resistance by reducing the spacing between the fibers with an overall increase in performance. Due to fiber hybridization, the significant positive synergy is observed in all CSPHFRC mix[24].

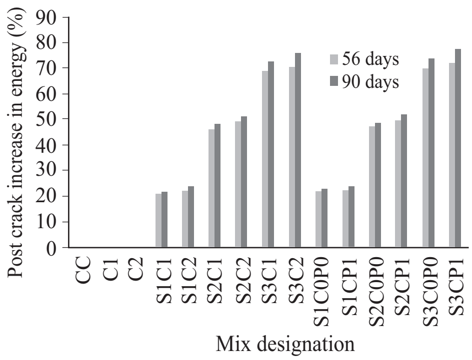
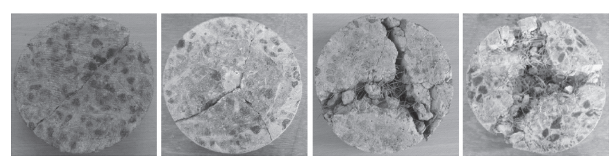


Fig. 6 Impact resistance (post crack resistance increase percentage) for all mixes at 56 and 90 Days

In CSHFRC mix, N1 increased from 2.87 to 4.62 times and 2.46 to 4.23 times at 56 days and 90 days respectively and N2 increased from 3.47 to 7.84 times and 3 to 7.42 times than control concrete at these days respectively. In CSPHFRC mix, N1 increased from 2.92 to 4.79 times, 2.51 to 4.38 times and N2 increased from 3.55 to 8.21 times, 3.08 to 7.77 times than control concrete at 56 and 90 days respectively. In control concrete, N1 and N2 values are 251 and 252 respectively at 28 days whereas in S3C1P1 mix, N1 and N2 values are 1460 and 2479 respectively at 28 days. There is a tremendous increase in impact resistance due to addition of hybrid fibers in quaternary blended concrete. These results reveal that the fiber hybridization enhanced the performance of the concrete against impact and also increase in post cracking strength than mono fiber system. The number of blows increased at 56 and 90 days than 28 days curing due to pozzolanic reaction; however, N1 and N2 values are almost same in control concrete in all respective ages due to its brittle behavior. These results are in accordance with previous results[6,8,27]. The percentage increase in post crack resistance is negligible in control concrete specimens.

Due to pozzolanic materials present in the mix, the impact resistances of concrete increased in terms of number of blows at longer curing periods. When compared to control concrete at 28 days, in CSHFRC mix, N1 increased from 3.96 to 6.39 times and 4.23 to 7.25 times at 56 and 90 days respectively and N2 increased from 4.79 to 10.83 times and 5.13 to 12.72 times at 56 and 90 days respectively. For CSPHFRC mix, N1 increased from 4.04 to 6.62 times and 4.31 to 7.52 times and N2 increased from 4.90 to 11.34 times and 5.28 to 13.33 times at 56 and 90 days respectively. When compared to C1 and C2 mixes at 28 days, N1 of respective mixes increased from 10.67% to 20.74% and 9.97% to 19.15% and N2 of the respective mixes increased from 10.64% to 20.68% and 9.95% to 19.10 % at 56 days and 90 days respectively. When compared to S1C1, S1C2, S2C1, S2C2, S3C1 and S3C2 mixes at 28 days, N1 of respective mixes increased from 8.03% to 15.20%, 6.94% to 13.47%, 10.31% to 30.67%, 10.64% to 28.48%, 14.40% to 30.04 %, and 13.68% to 29.06%, and N2 of the respective mixes increased from 9.43% to 17.32%, 7.29% to 15%, 11.89% to 34.16%, 11.75% to 31.61%, 16.44% to 34.94% and 15.48% to 35.58% at 56 days and 90 days respectively. When compared to S1C0P0, S1C1P1, S2C0P0, S2C1P1, S3C0P0 and S3C1P1mixes at 28 days, N1 of respective mixes increased from 8.22% to 15.58%, 7.02% to 13.64%, 11.57% to 32.07%, 11.37% to 29.21%, 14.29% to 29.93% and 13.84% to 29.32% and N2 of the respective mixes increased from 9.57% to 17.91%, 6.97% to 15.18%, 12.44% to 33.82%, 11.73% to 31.46%, 16.20% to 35.38% and 15.25% to 35.46% at 56 days and 90 days respectively. The significant positive synergy was observed in all the CSPHFRC when compared to CSHFRC and mono CFRC.



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

Fig. 7 Failure pattern of specimen (a) control; (b) CFRC; (c) CSHFRC; (d) CSPHFRC

The failure pattern of the control, CFRC, CSHFRC and CSPHFRC impact specimens are shown in Fig. 7. The control specimens failed in brittle manner and lost its structural integrity. This failure patterns is in agreement with the results of Rahmani, et al.[2]. Results of Mahmoud Nili and Afroughsabet[6,8] also supported this conclusion. The CFRC specimens failed into three pieces in brittle manner with thin cracks. The failure pattern was changed from single large crack to multiple cracks in CSHFRC and CSPHFRC specimens. The structural integrity was maintained in CSHFRC and CSPHFRC specimens than control and mono CFRC specimens. This property is very much needed for the concrete structures when subjected to the short duration dynamic loading. Fiber hybridization enhances the structural integrity of concrete under impact loading.

CONCLUSIONS

Based on the experimental results, the following conclusions are drawn:

- Due to pozzolanic materials present in the mix, the compressive, split tensile, flexural strength and impact resistance of concrete are increased in CFRC, CSHFRC and CSPHFRC compared to control concrete at longer curing periods. Between the two hybrid mixes, at 0.5% volume fraction of steel fibers, the significant positive synergy effect is observed in CSPHFRC mixes than CSHFRC mixes. However this synergy effect disappeared at 1% and 1.5% volume fraction of steel fibers along with carbon and PP fibers. CSHFRC mixes performed comparatively better than CSPHFRC mixes at 1% and 1.5% volume fraction of steel fibers.
- When compared to control concrete at 28 days, the maximum compressive strength improvement in CFRC is 58.72%, for CSHFRC 74.70% and for CSPHFRC 70.24 % at 90 days. The maximum split tensile strength improvement in CFRC is 30%, for CSHFRC 173.33% and for CSPHFRC 163.61% at 90 days respectively. The maximum flexural strength improvement in CFRC is 78.65%, for CSHFRC 273.55% and for CSPHFRC 268.91% at 90 days respectively. This strength improvement at longer curing periods is due to pozzolanic reactions leading to increase in strength.
- Like control concrete, CFRC mixes also performed poorly against impact loads whereas CSHFRC and CSPHFRC specimens performed well against impact loads. Their impact resistance and post crack resistance increased when fiber content increased. The percentage increase in post crack resistance is negligible for control concrete and CFRC specimens whereas the same is higher in all CSHFRC and CSPHFRC system. The maximum percentage increase in post crack resistance is 77.86% in S3C1P1 (1.5% steel +0.25% carbon+ 0.25% PP) at 90 days.
- When compared to control concrete at 28 days, number of blows required to cause first crack (N1) increased from 4.23 to 7.25 times and ultimate failure (N2) increased from 5.13 to 12.72 times for CSHFRC and the same values were increased from 4.31 to 7.52 times and 5.28 to 13.33 times for CSPHFRC at 90 days respectively.

From the test results, S1C0P0 (0.5% steel +0.125% carbon+ 0.125% PP) and S1C1P1 (0.5% steel +0.25% carbon+ 0.25% PP) mixes can be considered as the most appropriate steel-carbon-PP hybrid fiber combination for compressive, split tensile and flexural strength and also S3C1P1 mix can be considered as the most appropriate hybrid combination for impact resistance of the concrete irrespective of the curing periods. It can be concluded that incorporation of SCMs in blended cement concrete with hybrid fibers has resulted in improvement of all the mechanical properties considered including the impact resistance leading to the economical and environmental benefits.

REFERENCES

1. Kathirvel, P., “Strength and Durability Properties of Quaternary Cement Concrete Made with Fly Ash, Rice Husk Ash and Limestone Powder”, *Arab. Jl. for Sci. and Engg.*, Vol. 38, 2013, pp 589–598.
2. Rahmani, T., “Statistical and experimental analysis on the behavior of fiber reinforced concretes subjected to drop weight test”, *Construct. and Build. Mat.*, Vol. 37, 2012, pp 360–369.
3. Holschemacher, K., Mueller, T. and Ribakov, Y., “Effect of steel fibres on mechanical properties of high strength concrete”, *Mat. and Des.*, Vol. 31, 2010, pp 2604–2615.
4. Xu, B.W., Shi, H.S., “Correlations among mechanical properties of steel fiber reinforced concrete”, *Construct. and Build. Mat.*, Vol. 23, 2009, pp 3468–3474.
5. Yao, W., Li, J. and Wu, K., “Mechanical properties of hybrid fiber-reinforced concrete at low fiber volume fraction”, *Cem. and Conc. Res.*, Vol. 33, 2003, pp 27–30.
6. Nili, M. and Afroughsabet, V., “Combined effect of silica fume and steel fibers on the impact resistance and mechanical properties of concrete”, *Intl. Jl. of Impact Engg.*, Vol. 37, 2010, pp 879–886.

7. Koksal, F., "Combined effect of silica fume and steel fiber on the mechanical properties of high strength concretes", *Construct. and Build. Mat.*, Vol. 22, 2008, pp 1874–1880.
8. Nili, M. and Afroughsabet, V., "The effects of silica fume and polypropylene fibers on the impact resistance and mechanical properties of concrete", *Construct. and Build. Mat.*, Vol. 24, 2010, pp 927–933.
9. Kayali. O., "Effect of high volume fly ash on mechanical properties of fiber reinforced concrete", *Mat. and Structs./Matériaux et Construct.*, Vol. 37, 2004, pp 318–327.
10. De Gutiérrez, R.M., Diaz, L.N. and Delvasto, S., "Effect of pozzolans on the performance of fiber-reinforced mortars", *Cem. and Conc. Compos.,* Vol. 27(5), 2005, pp 593–8.
11. Walton, P.L. and Majumdar, A.J., "Cement-based composites with mixtures of different types of fibres", *Composites*, Vol. 6(5), 1975, pp 209–16.
12. Sivakumar, A. and Santhanam, M., "Mechanical properties of high strength concrete reinforced with metallic and non-metallic fibres", *Cem. and Conc. Compos.*, Vol. 29, 2007, pp 603–608.
13. Qian, C.X. and Stroeven, P., "Development of hybrid polypropylene-steel fibre-reinforced concrete", *Cem. and Conc. Res.*, Vol. 30, 2000, pp 63–69.
14. Banthia, N., Sappakittipakorn, M., "Toughness enhancement in steel fiber reinforced concrete through fiber hybridization", *Cem. and Conc.Res.*, Vol. 37, 2007, pp 1366–1372.
15. Chen, B. and Liu, J., "Contribution of hybrid fibers on the properties of the high-strength lightweight concrete having good workability", *Cem. and Conc. Res.*, Vol. 35, 2005, pp 913–917.
16. Rashiddadash, P., Ramezanianpour, A.A and Mahdikhani, M., "Experimental investigation on flexural toughness of hybrid fiber reinforced concrete (HFRC) containing metakaolin and pumice", *Construct. and Build. Mat.*, Vol. 51, 2014, pp 313–20.
17. IS 10262-2009, "Indian Standard Guidelines for concrete mix design proportioning", *Bureau of Indian Standards*, New Delhi, India, 2009.
18. IS 1199-1959, (Reaffirmed 1999), "Indian Standard Methods of Sampling and Analysis of Concrete", *Bureau of Indian Standards*, New Delhi, India.
19. IS 516-1959, (Reaffirmed 1999) Edition 1.2 (1991-07), "Indian Standard Methods of Tests for Strength of Concrete", Bureau of Indian Standards, New Delhi, India.
20. IS 5816-1999, "Indian Standard Splitting Tensile Strength of Concrete- Method of Test", *Bureau of Indian Standards*, New Delhi, India.
21. ACI 544.2R-89 (Reapproved 2009), "Measurement of Properties of Fiber Reinforced Concrete", *Am. Conc. Inst.*, Reported by ACI Committee 544, Farmington Hills, Michigan.
22. Alavi Nia, A., Hedayatian, M., Nili, M. and Afroughsabet, V., "An experimental and numerical study on how steel and polypropylene fibers affect the impact resistance in fiber-reinforced concrete", *Intl. Jl. of Impact Engg.*, Vol. 46, 2012, pp 62–73.
23. Mo, K.H., Yap, S.P., Alengaram, U.J., Jumaat, M.Z. and Bu, C.H., "Impact resistance of hybrid fibre-reinforced oil palm shell concrete", *Construct. and Build. Mat.*, Vol. 50, 2014, pp 499–507.
24. Ramesh Kanagavel and Arunachalam Kalidass, "Mechanical Properties of Hybrid Fiber Reinforced Quaternary Concrete", *Gradevinar*, Vol. 69, No. 1, 2017, pp 1–10.
25. Banthia, N., Majdzadeh, F., Wu, J. and Bindiganavile, V., "Fiber synergy in Hybrid Fiber Reinforced Concrete (HyFRC) in flexure and direct shear", *Cem. and Conc. Compos.*, Vol. 48, 2014, pp 91–97.
26. Sengul, O. and Tasdemir, M.A., "Compressive strength and rapid chloride permeability of concretes with ground fly ash and slag", *Jl. of Mat. in Civ. Engg.*, Vol. 21(9), 2009, pp 494–501.
27. Dawood, E.T. and Ramli, M., "Mechanical properties of high strength flowing concrete with hybrid fibers", *Construct. and Build. Mat.*, Vol. 28, 2012, pp 193–200.

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