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# Mechanical properties of hybrid fibre reinforced quaternary concrete

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## Mechanical properties of hybrid fibre reinforced quaternary concrete

Quaternary blending cement concrete with fibres is studied in terms of compressive, split tensile, and flexural strength properties, and impact resistance. Fly ash, rice husk ash, and limestone powder, are used as partial replacement of cement. Steel, carbon, and polypropylene fibres, are used in different fractions. The results show that the steel-carbon and steel-carbon-polypropylene hybrid fibre reinforced concretes perform better with regard to compressive, split tensile, and flexural strength properties, and impact resistance.

Key words:
quaternary blending cement, hybrid fibres, compressive strength, split tensile strength, flexural strength, impact resistance, post crack resistance

Izvorni znanstveni rad

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## Mehanička svojstva hibridnog mikroarmiranog betona s miješanim cementom

U radu su promatrane tlačna, vlačna, savojna i udarna čvrstoća hibridnih mikroarmiranih betona s dodatkom vlakana. Kao djelomična zamjena cementa upotrijebljeni su leteći pepeo, pepeo rižinih ljuski i vapnenac. Korištena su čelična, karbonska i polipropilenska vlakana u različitim udjelima. Rezultati su pokazali da hibridni mikroarmirani betoni s čeličnim i karbonskim vlaknima, odnosno čeličnim, karbonskim i polipropilenskim vlaknima imaju bolja tlačna, vlačna i savojna svojstva te veću udarnu čvrstoću.

Ključne riječi:
miješani cementi, hibridni mikroarmirani beton, tlačna čvrstoća, vlačna čvrstoća cijepanjem, savojna čvrstoća, udarna čvrstoća, postpukotinsko ponašanje

Wissenschaftlicher Originalbeitrag

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## Mechanische Eigenschaften faserverstärkten Hybridbetons mit Mischzement

In dieser Arbeit werden Druck-, Zug-, Biege- und Stoßfestigkeit faserverstärkten Hybridbetons untersucht. Teilweise wurden dabei Flugasche, Reisschalenasche und Kalkstein als Zementersatz verwendet. Es wurden Stahl-, Carbon- und Polypropylenfasern in verschiedenen Anteilen eingesetzt. Die Resultate haben gezeigt, dass faserverstärkter Hybridbeton mit Stahl- und Carbonfasern, bzw. mit Stahl-, Carbon- und Polypropylenfasern bessere Druck-, Zug- und Biegeeigenschaften sowie eine bessere Stoßfestigkeit hat.

Schlüsselwörter:
Mischzement, Hybridbeton, Druckfestigkeit, Spaltzugfestigkeit, Biegefestigkeit, Stoßfestigkeit, Rissverhalten

## 1. Introduction

Supplementary Cementitious Materials (SCMs) are nowadays used in concrete to reduce the cement quantity and improve its properties [1]. SCMs are effectively utilized by many researchers since they improve properties of the blended cement concrete. Kathirvel et al [2] investigated an optimum percentage of SCMs like Fly Ash (FA), Rice Husk Ash (RHA) and Lime stone Powder (LP) in a quaternary mix, from the aspects of strength and durability. They concluded that the compressive, split tensile, and flexural strength values, and the durability of concrete increased in a quaternary blending cement with 20 % FA, 10 % LP, and 10 % RHA. Despite the benefits the concrete made with SCMs brings to concrete structures, it is not promising when subject to the short-time impact and dynamic load. Due to its poor tensile characteristics, it fails in brittle manner in case of such loads. Impact resistance is important when they are subjected to dynamic loads such as falling objects in industrial buildings and airport runways, impact by missiles, impulsive loads due to air blasts, earthquake and ocean waves, etc. [3]. The addition of fibres to concrete improves its static flexural strength, impact strength, tensile strength, ductility, and flexural toughness [4]. Steel, carbon, and polypropylene fibres are generally used in concrete [5]. Available studies focusing on the addition of steel fibres [6] and polypropylene fibres [7] point to the improvement of mechanical properties and energy absorption of concrete. The addition of carbon fibres improves the cracking resistance and fatigue life of concrete [8]. Carbon fibres are characterized by superior mechanical and thermal properties, and chemical stability [9]. Thus in the Fibre Reinforced Concrete (FRC), the weaker matrix is reinforced with strong fibres to produce a composite of superior properties. There has been much enthusiasm recently in the field of FRC for the development of hybrid fibre systems where two or more types of fibres are combined. The addition of one type of fibres to concrete can bring some improvements to the composite's properties. However, when the fibres are added as a hybrid having two or more combinations, the hybrid composites exhibit more attractive engineering properties in comparison with the addition of a single type of fibres in the composites [5]. Past research findings clearly demonstrate that the incorporation of different kinds of hybrid fibres in concrete improves the engineering performance of concrete and results in better mechanical properties, compared to the mono-fibre reinforced concrete [5, 10-13].

A review of literature reveals that a number of investigations have been conducted to study the effect of SCMs on concrete properties, with a separate focus on mechanical properties of the single fibre reinforced concrete, and hybrid fibre reinforced concrete. A limited research has however been carried out to investigate the influence of fibre addition in mono form and hybrid form, with incorporation of SCMs. The addition of steel-carbon and steel-carbon-polypropylene hybrid fibres in quaternary blending of fly ash, RHA and LP cement concrete, has not been investigated so far. Therefore, an attempt has been made in this investigation to study the combined effect of mono carbon fibres, carbon-steel, and carbon-steel-polypropylene hybrid fibres, with the addition of fly ash, RHA and LP, on mechanical properties.

## 2. Experimental program

### 2.1. Material properties

The Ordinary Portland Cement (OPC) having minimum compressive strength of 53 MPa at 28 days, with the specific gravity of 3.11, was used for all concrete mixes. River sand with specific gravity of 2.60 was used as fine aggregate, and hard broken granite stone passing through 12.5 mm and retained on 4.75 mm sieve, with specific gravity of 2.70, was used as coarse aggregate. FA was obtained from Thermal Power Station located at Tuticorin, Tamil Nadu, India. RHA with specific gravity of 2.3, and locally available LP with specific gravity of 2.80, were used. Ordinary potable water was used for concrete preparation. Chemical compositions of FA, RHA and LP are given in Table 1. Low carbon hooked end steel fibres, fibrillated polypropylene fibres, and carbon fibres, were used in this investigation. They are shown in Figure 1. The steel fibre 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

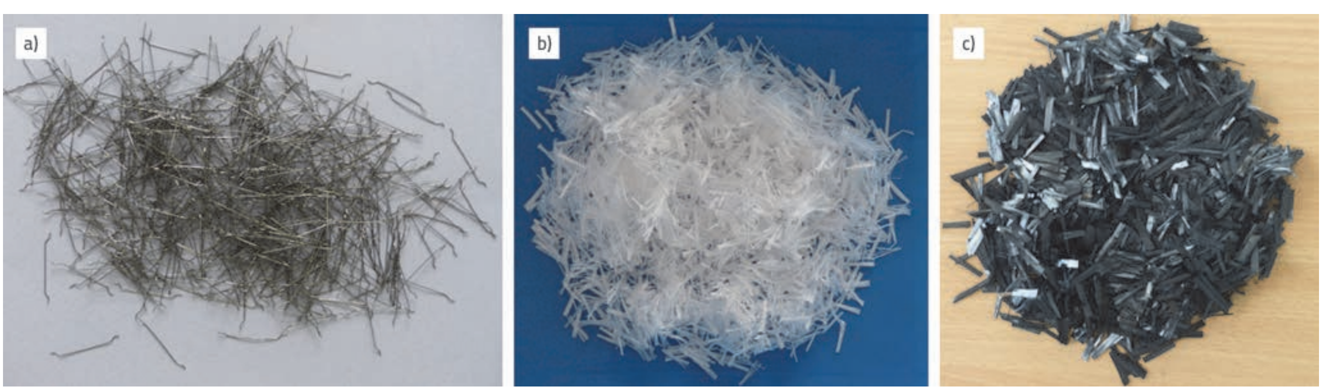

**Figure 1. Photos of fibres: a) steel; b) fibrillated polypropylene; c) carbon**

MPa. The fibrillated Polypropylene fibre (PP) had a length of 20 mm, diameter of 0.04mm, specific gravity of 0.91, and tensile strength ranging between 350 MPa and 450 MPa. The length of a carbon fibre was 12 mm, the diameter was 11 micron, and its carbon content was 95 %. The tensile strength and bulk density of carbon fibres amounted to 4300 MPa, and 554 g/litre, respectively.

**Table 1. Chemical composition of FA, RHA and LP**

| Chemical composition [%] | FA (Flay ash) | RHA (Rice husk ash) | LP (Lime stone powder) |
|---|---|---|---|
| $SiO_2$ | 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 |

## 2.2. Mixing proportion

The plain concrete mix proportion was designed as per IS 10262-2009 [14] for the M30 grade concrete. The designed mix proportion was 1:1.61:2.25, with the w/c ratio of 0.48. The quaternary mix was treated as the control mix in which the OPC was partially replaced with 20 % FA, 10 % RHA, and 10 % LP by weight of cement based on the earlier study conducted by Kathirvel et al [2]. The mix proportion given in Table 2 was used for all concrete mixes. Carbon fibres were added individually at 0.25 % and 0.5 % weight fractions of cementitious materials. When carbon fibres were added in hybrid form with polypropylene fibres, the total weight fraction was maintained at 0.25 % and 0.5 % of the weight of cementitious materials. The steel fibres were added at 0.5 %, 1 %, and 1.5 % volume fractions in all carbon, carbon-polypropylene hybrid systems. Different proportion of fibres in the mix is shown in Table 3.

**Table 2. Mix proportion including SCMs**

| Material | Proportion | Quantity [kg/m$^3$] |
|---|---|---|
| Cement | 0.6 | 260.72 |
| Fly ash | 0.2 | 86.91 |
| Rice husk ash | 0.1 | 43.45 |
| Lime stone powder | 0.1 | 43.45 |
| Fine aggregate | 1.61 | 698.90 |
| Coarse aggregate | 2.25 | 977.92 |
| Water | 0.48 | 208.6 |

**Table 3. Fibre combinations in mixes**

| Number of mixing | Mix designation | Steel fibre $V_f$ [%] | Polypropylene fibre $W_f$ [%] | Carbon fibre $W_f$ [%] |
|---|---|---|---|---|
| 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 | | | | |

## 2.3. Mixing and casting

The coarse and fine aggregates were initially mixed for one minute in the concrete mixer. The cement, FA, RHA and LP were added in the mixer, and the dry mixing was conducted for about 2 minutes. Then water was added and mixing continued for another 5 minutes. Finally, the specified amount of fibres was added to the mixtures and mixed for 5 minutes to achieve a uniform distribution. The Vee - Bee consistometer test was conducted to measure the workability of different fibre combinations. At 1.5 % volume fraction of steel fibres, the workability was decreased and the balling effect of fibres occurred. It was accelerated when the carbon and polypropylene fibres were mixed with steel fibres. The freshly mixed concrete was cast into the moulds and compacted with table vibrator to measure properties of hardened concrete. The specimens were cast in cube (150 mm x150 mm x 150 mm), cylinder (150 mm diameter x 300 mm length) and beam (100 mm x100 mm x 500 mm) moulds for the compressive, split tensile, and flexural strength tests, respectively. Cylindrical disc specimens (150 mm in diameter and 64 mm in thickness) were used for impact tests. After 24 hours, the specimens were demoulded and cured in water tank until the age of testing.

## 2.4. Testing methodology

The workability of the fresh concrete mixture was measured using the Vee - Bee consistometer test as per IS 1199-1959 (R1999) [15]. The compressive strength test was conducted on cube specimens, and the flexural strength test was conducted on beam specimens with two point loading as per IS 516-1999 [16]. The split tensile strength test was carried out on cylinder specimens as per IS 5816-1999 [17]. The impact resistance of the concrete specimen was determined as per ACI Committee Report 544.2R-89 drop weight impact test [18]. The impact test specimens (150 mm diameter x 64 mm thick cylindrical discs) were cut from the cylinders specimen measuring 150 mm in diameter and 300 mm in length, and then prepared. The impact specimen was placed on a base plate with four positioning lugs of the impact testing equipment. The 4.54 kg hammer weight was dropped from the height of 457 mm repeatedly on the 63.5 mm diameter steel ball, which was placed at the centre 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 Figure 2. The impact energy absorption capacity of the concrete specimen was calculated [19, 20] using the equation Eq.(1).

$$E_{imp} = N \cdot m \cdot g \cdot h \qquad (1)$$

where:
$E_{imp}$ - impact energy [J]
m - mass of drop hammer [kg], g = 9,81 m/s$^2$
h - releasing height of drop hammer [m]
N - number of blows.

The compressive, split tensile, and flexural strength tests were carried out on three specimens and the impact resistance test was performed on five specimens at the age of 28 days, and the average values were calculated. The test results were compared with the control concrete specimen that contained cement replacement materials without fibres.

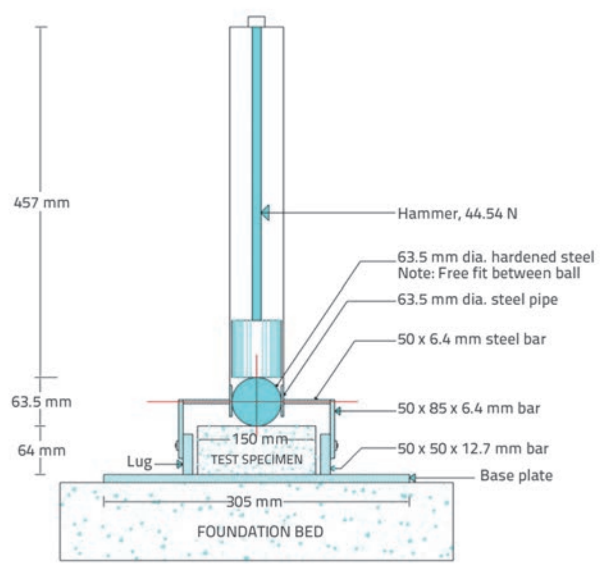


**Figure 2. Schematic diagram of impact resistance test setup**

## 3. Results and discussion

The workability, compressive strength, split tensile strength, and flexural strength values, and the impact resistance results are presented in Table 4. The increased percentage of compressive, split tensile, and flexural strength as related to control concrete at 28 days is shown in Figure 3 to 5.

### 3.1. Workability

The Vee-Bee test gives a more accurate indication of the FRC workability than the standard slump test and the compacting factor test [21]. FRC mixtures respond well to vibration even at a very low slump [18]. The Vee-Bee test results are shown in Table 4 for all concrete mixes. The addition of carbon, steel and polypropylene fibres in fresh concrete increased the Vee-Bee time. And also, when the fibre content was increased, the Vee-Bee time further increased indicating a decrease in the workability of concrete. The Vee-Bee time ranged between 5 and 8 seconds for the Carbon Fibre Reinforced Concrete (CFRC). When steel fibres were introduced in the CFRC mix, the Vee-Bee time was further increased. This result is in accordance with the Tayfun Uygunoglu findings [21] according to which the addition of steel fibres increased the Vee-Bee time ranging between 2 seconds and 70 seconds for the 0-1.3 % fibre volume fraction. In the present study, the Vee-Bee time ranged between 11 seconds and 67 seconds for the Carbon - Steel Hybrid Fibre Reinforced Concrete (CSHFRC). When fibrillated polypropylene fibres were introduced in the CSHFRC mix, the Vee-Bee time was further increased. In the Carbon-Steel-PP Hybrid Fibre Reinforced Concrete (CSPHFRC), the Vee-Bee time ranged between 13 seconds and 70 seconds. The addition of hooked ended steel fibres and fibrillated polypropylene fibres increased the Vee-Bee time. Similar findings were reported by Ozgur Eren and Khaled Marar [22] and also by Karahan O and Atis C.D [23]. At 1.5 % volume fraction of steel fibres, the workability was decreased and the balling effect of fibres occurred. It was accelerated when the carbon and polypropylene fibres were mixed with steel fibres. The addition of fibrillated polypropylene fibres can form a network structure in concrete which restrains mixture flow. Because of a large number and large surface area of fibres, they absorb more cement paste that wraps around them, and affect the viscosity of concrete mixes, causing a decreased workability. Due to this, the workability was further decreased and the balling effect of fibres occurred and hence the concrete mix was not fully compacted. This effect was more dominant in CSPHFRC mixes compared to CSHFRC mixes.

### 3.2. Compressive strength

The compressive strength test results are shown in Table 4. The percentage of increase in compressive strength compared to control concrete at 28 days is shown in Figure 3. Test results

**Table 4. Results of workability, compressive strength, split tensile strength, flexural strength and impact resistance**

| Mix designation | Compressive strength [N/mm²] | Split tensile strength [N/mm²] | Flexural strength [N/mm²] | Vee -Bee time [s] | Udarna čvrstoća | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Number of blows | | Impact energy [Nm] | | Percentage increase in post crack resistance [(N2-N1)/ (N1)] x 100 |
| | | | | | First crack (N1) | Failure (N2) | First crack | Failure | |
| CC | 37.16 | 3.60 | 4.31 | 3 | 251 | 252 | 5108.8 | 5129.1 | 0.4 |
| C1 | 47.96 | 3.98 | 5.50 | 5 | 675 | 677 | 13738.7 | 13779.4 | 0.3 |
| C2 | 44.44 | 4.17 | 5.68 | 8 | 752 | 754 | 15305.9 | 15346.6 | 0.3 |
| S1C1 | 48.53 | 5.00 | 7.20 | 11 | 921 | 1103 | 18745.7 | 22450.0 | 19.8 |
| S1C2 | 50.44 | 5.28 | 7.58 | 15 | 980 | 1193 | 19946.5 | 24281.8 | 21.7 |
| S2C1 | 54.71 | 6.46 | 9.54 | 20 | 1115 | 1607 | 22694.3 | 32708.2 | 44.1 |
| S2C2 | 52.98 | 6.84 | 9.90 | 28 | 1194 | 1762 | 24302.2 | 35863.0 | 47.6 |
| S3C1 | 50.22 | 7.89 | 12.88 | 45 | 1285 | 2135 | 26154.4 | 43454.9 | 66.1 |
| S3C2 | 49.69 | 8.28 | 13.32 | 67 | 1411 | 2364 | 28718.9 | 48115.9 | 67.5 |
| S1C0P0 | 49.11 | 5.12 | 7.36 | 13 | 937 | 1128 | 19071.3 | 22958.9 | 20.4 |
| S1C1P1 | 52.22 | 5.38 | 7.66 | 17 | 997 | 1219 | 20292.5 | 24811.0 | 22.3 |
| S2C0P0 | 53.33 | 6.14 | 9.44 | 24 | 1132 | 1656 | 23040.3 | 33705.5 | 46.3 |
| S2C1P1 | 52.80 | 6.68 | 9.78 | 36 | 1205 | 1799 | 24526.1 | 36616.1 | 49.3 |
| S3C0P0 | 49.82 | 7.64 | 12.72 | 47 | 1323 | 2210 | 26927.8 | 44981.4 | 67.0 |
| S3C1P1 | 48.62 | 7.96 | 13.16 | 70 | 1460 | 2479 | 29716.2 | 50456.6 | 69.8 |

reveal that the compressive strength of CFRC, CSHFRC and CSPHFRC is higher than that of the control concrete at 28 days. The compressive strength improvement in CFRC ranges from about 20 to 29 %, in CSHFRC from about 31 to 47 %, and in CSPHFRC from about 31 to 44 % compared to the control concrete at 28 days, respectively. In CFRC, the compressive strength was improved by up to 29 % compared to control concrete at 28 days. Similar findings were made by Baeza. F.J. et al [24] where the addition of carbon fibres improved the compressive strength by up to 25 % compared to control concrete, at 28 days. The compressive strength improvement for the CSHFRC mix S1C1 is about 31 %, and it is about 36 % for the mix S1C2, compared to the control mix, at 28 days. These results are in accordance with previous results. Chen B. and Liu J. [13] reported that the compressive strength increased by 27.6 % when steel and carbon fibres were added to the high strength light weight concrete at 28 days. Wu Yao et al [5] reported that the compressive strength improvement was 31.4 % in carbon-steel hybrid composites compared to the control mix, at 28 days. The highest strength was achieved in the CSHFRC mix S2C1. The results were also compared between the CSPHFRC and CSHFRC systems. At 0.5 % volume fraction of steel fibres, a better positive synergic effect was observed only at the CSPHFRC system mixes S1C0P0 and S1C1P1, compared to the CSHFRC mixes S1C1 and S1C2. The maximum strength increase was up to 32 % and 41 % in the mixes S1C0P0 and S1C1P1, respectively, as compared to the control mix, at 28 days. However, the negative synergy was observed in all other CSPHFRC mixes compared to all CSHFRC mixes at 1 % and 1.5 % volume fraction of steel fibre. The compressive strength was lower in mixes S2C0P0 to S3C1P1, as compared to S2C1 to S3C2 mixes. The hybridization was less effective at higher fibre dosage rates [25]. At a higher percentage of hybridization, a higher amount of fibres produces 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.

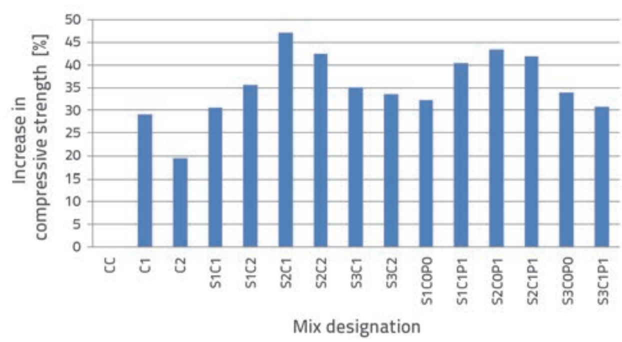


**Figure 3. Percentage increase in compressive strength at 28 days**

### 3.3. Split tensile strength

The split tensile strength test results are depicted in Table 4, and the percentage of increase at 28 days in the split tensile strength compared to the control concrete, is shown in Figure 4. It can be seen that the split tensile strength increases with an increase of the fibre fraction in the mixes. At 28 days, the split tensile strength increases in CFRC from about 11 to 16 %, and in CSHFRC from about 39 to 130 %, and also in CSPHFRC from about 42 to 121 %, compared to the control concrete, respectively. The maximum increase in the split tensile strength is 130 % compared to the control concrete in the CSHFRC mix S3C2. At 28 days, the split tensile strength improvement in the CSHFRC mix S1C1 is about 39 %, while it is about 47 % in the mix S1C2 compared to the control concrete. Similar findings were reported by Chen. B and Liu. J [13] who found that the split tensile strength increased by 38.3 % when the steel and carbon fibres were added to the High Strength Lightweight Concrete at 28 days. Wu Yao et al. [5] reported that the split tensile strength improvement amounted to 36.5 % in carbon-steel hybrid composites compared to the control mix, at 28 days. The maximum split tensile strength was achieved in the CSHFRC mix S3C2. Wu Yao et al [5] reported that carbon–steel fibres provide the highest split tensile strength. When the results were also compared with the CSPHFRC and CSHFRC systems, the positive synergy effect was observed only in the mixes S1C0P0 and S1C1P1 compared to mixes S1C1 and S1C2 at 0.5 % volume fraction of steel fibres. The maximum percentage of increase at 28 days is up to 42 % and 49 % in the mixes S1C0P0 and S1C1P1, respectively, compared to the control concrete. The strength development might be due to the presence of SCMs, high modulus steel and carbon fibres in the matrix, anchoring effect of the hooked end steel fibres, interlocking effect of cross linked network fibrillated polypropylene fibres with the matrix, and the availability of more polypropylene fibres at the critical section due to its low specific gravity. At 1 % and 1.5 % volume fraction of steel fibres, the negative synergy was observed in CSPHFRC mixes compared to CSHFRC mixes. The CSHFRC mixes provided the higher strength than the CSPHFRC mixes. Similar findings were previously reported by Chen B. and Liu J. [13] who established that the carbon-steel hybrid fibre combination provided a better effect than the carbon-PP- steel fibre combination. At a higher percentage of hybridization, the balling effect of fibres occurred and, hence, the concrete mix was not fully compacted. Due to this, there was a deficiency in the transition zone between the fibres and the paste with a lot of porosity and, hence, the split tensile strength was reduced. This effect was more dominant in CSPHFRC mixes than in CSHFRC mixes. It can be seen from test results that, due to a positive synergy effect, CSHFRC system performs well in all volume fractions of steel fibres whereas the CSPHFRC system performs well only in the 0.5 % volume fraction of steel fibres. If the percentage of increase in compressive strength and split tensile strength is compared, it can be seen that the percentage of increase is greater in case of the split tensile strength compared to the compressive strength. The same was established in earlier investigations during which it was also revealed that fibres play a greater role in the increase of tensile strength than in the increase of compressive strength.

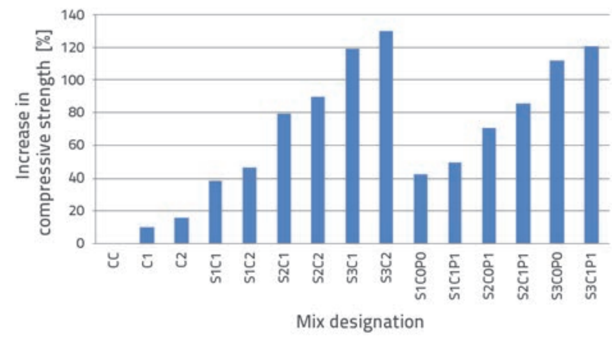


**Figure 4. Percentage of increase in split tensile strength at 28 days**

### 3.4. Flexural strength

The flexural strength test results for various mixes are presented in Table 4, and the increase in the percentage of flexural strength compared to the control concrete at 28 days, is shown in Figure 5. It can be observed that the flexural strength increases with an increase in the fibre content fraction. At 28 days, the flexural strength increases in CFRC from 28 to 32 %, in CSHFRC from 67 to 209 %, and in CSPHFRC from 71 to 205 %, compared to results for the control concrete. Due to synergic effect, the carbon-steel hybrid system performs well in all volume fractions of steel fibres. In the CSPHFRC system, the positive synergic effect is observed only in the mixes S1C0P0 and S1C1P1 compared to the mixes S1C1 and S1C2 at the 0.5 % volume fraction of steel fibres. At 28 days, the maximum percentage of increase is about 71 % and 78 % for S1C0P0 and S1C1P1, respectively, compared to the control concrete.

The reason for strength development is the same as for the split tensile strength. The negative synergy was observed in CSPHFRC mixes compared to CSHFRC mixes, at the 1 % and 1.5 % volume fraction of steel fibres. The CSHFRC mixes exhibited the higher strength than the CSPHFRC mixes. The maximum percentage of increase in flexural strength of the CSHFRC mix S3C2 is about 209 % compared to the control concrete. The test results revealed that, due to a positive synergic effect, CSHFRC performs well in all volume fractions of steel fibres, while CSPHFRC performs well only in the 0.5 % volume fraction of steel fibres. If the percentage of increase is compared between the flexural strength and compressive strength, it can be seen that the percentage of increase in flexural strength is greater than that of the compressive strength.

This is similar to the findings related to the split tensile strength. However, the percentage of increase is higher than that of the split tensile strength.

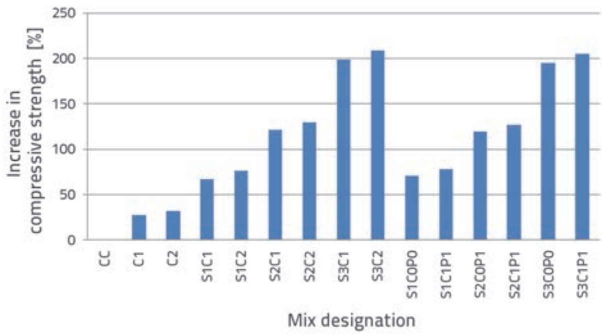


**Figure 5. Percentage of increase in flexural strength at 28 days**

### 3.5. Impact test

The impact resistance of concrete mixes is shown in terms of the number of blows required to cause the first crack (N1) and ultimate failure (N2), cf. Table 4. The numbers of blows N1 and N2 are shown in Figure 6 for various combinations. The percentage of increase in the post crack resistance for all mixes is shown in Table 4 and Figure 7. The percentage of increase in the post crack resistance is negligible for the control concrete and CFRC specimens. For the control concrete, N1 and N2 values are almost the same due to its brittle failure [6, 26]. The impact resistance of CFRC, SCHFRC and SCPHFRC increases with an increase in fibre content. Even though the number of blows N1 and N2 was higher for CFRC specimens than for the control concrete, the failure occurred in the brittle manner, which is similar to behaviour exhibited by the control concrete. At 28 days the post crack resistance of SCHFRC increases from 19.8 % to 67.5 %, and from 20.4 % to 69.8 % for SCPHFRC, compared to the control concrete. The maximum percentage of increase in the post crack resistance amounts to 69.8 % for the SCPHFRC mix S3C1P1, compared to the control concrete. This increase is due to a higher fibres fraction. At a higher fibre percentage, the impact specimens yield by the fibre pull out failure. Impact specimens absorbed more energy during the fibre pull out along the failure crack [27]. At the 1.5 % volume fraction of steel fibres, the percentage of increase in the post crack resistance is 67.5 % for the SCHFRC mix S3C2. Semsi Yazıcı et al. [28] reported that the best performance of the Steel Fibre Reinforced Concrete (SFRC) exposed to impact load was obtained at the 1.5 % volume fraction of steel fibres in the concrete. The percentage of increase in the post crack resistance of 67.5 % for the mix S3C2 containing steel and carbon fibres is higher than the value of 50 % previously reported for the SFRC mix impact specimen [29] in the absence of carbon fibre. In this study, the addition of carbon fibres to steel fibres may be the reason for an increase in the percentage of post crack resistance. The addition of carbon fibres along with steel fibres to concrete increased the fracture toughness of the interfacial zone between the steel fibres and the matrix [30]. The percentage of increase in the post crack resistance is higher in all SCPHFRC mixes, compared to the SCHFRC and the mono fibre system. The addition of low modulus polypropylene fibres to the high modulus steel and carbon fibres may also be the reason for an increase in the percentage of post crack resistance. Due to fibre hybridization, a significant positive synergy was observed in all SCPHFRC mixes.

In the CFRC mix, N1 increased from 2.69 by 3 times, and N2 increased from 2.69 by 2.99 times, compared to the control concrete. In the SCHFRC mix, N1 increased from 3.67 by 5.62 times and N2 increased from 4.38 by 9.38 times, compared to the control concrete at 28 days. In the SCPHFRC mix, N1 increased from 3.73 by 5.82 times, and N2 increased from 4.48 by 9.84 times compared to the control concrete at 28 days. in the SCPHFRC mix S3C1P1, the maximum values of N1 and N2 are by 5.82 and 9.84 times greater than those of the control concrete. These values are higher than the previously reported values of N1 and N2 where the 4 and 8.5 fold increase was registered in the steel fibre reinforced lightweight aggregate concrete impact specimen, compared to the lightweight aggregate concrete at 28 days with the volume fraction of 1.5 % [31] in the absence of PP fibre and carbon fibre. When only steel fibres (macro fibres) are used in concrete, the fibre spacing is higher. On the other hand, when polypropylene and carbon fibres (micro fibres) are mixed with steel fibres (macro fibres) either individually or in a combined form, they play a better role in increasing the impact resistance by reducing the spacing between the fibres, with an overall increase in performance. Adding two or more types of fibres made complementary and additional contributions to the performance of the concrete mix. PP and carbon micro fibres, combined with steel macro fibres, produced an increase in impact resistance beyond what was achievable with the steel macro fibres and carbon fibres alone. This is due to the fact that the PP micro fibres delayed the formation of cracks, the development of which typically governed the strength of plain concrete and concrete with the low fibre content. The significant positive synergy was observed in all SCPHFRC mixes, compared to the SCHFRC and mono CFRC.

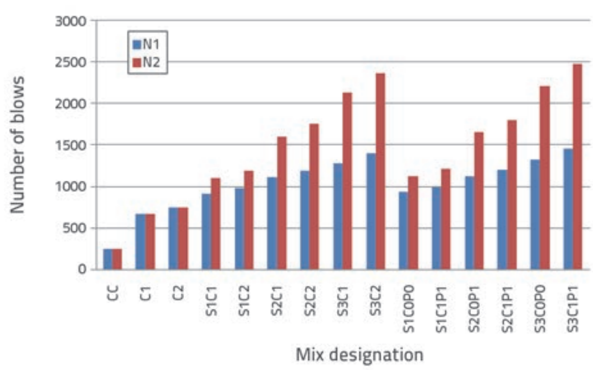


**Figure 6. Impact resistance at first crack and ultimate failure**

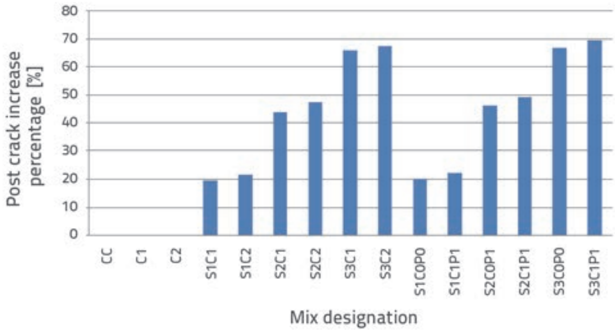


**Figure 7. Impact resistance (post crack resistance increase percentage) for all mixes**

The failure pattern of the control, CFRC, SCHFRC and SCPHFRC specimens after the impact test is shown in Figure 8. The control specimens failed suddenly in a brittle manner and lost their structural integrity. This failure patterns is in agreement with the results of Tara Rahmani et al [32]. Results of Mahmoud Nili and V. Afroughsabet [6, 7] also support this conclusion. The CFRC specimens were fractured into three pieces in a brittle manner, with thin cracks. The multiple cracking failure pattern was observed in SCHFRC and SCPHFRC specimens. As compared to the control and mono CFRC specimens, the failure pattern In SCHFRC and SCPHFRC changed from a single large crack to multiple cracks while the structural integrity was retained. The structural integrity is very much needed for the concrete structures when subjected to the short-time dynamic loading. Hybridization resulted in an increased structural integrity of concrete under impact load.

## 4. Conclusions

Based on experimental results, the following conclusions can be made:

- The workability decreases as the fibre content increases, both in mono-fibre and hybrid-fibre reinforced concrete mixes.
- At 28 days, the addition of hybrid fibres enhanced the compressive strength, the split tensile strength and flexural strength, compared to the control concrete. There is a positive synergy in SCPHFRC mixes at the 0.5 % volume fraction of steel fibres, compared to SCHFRC mixes. However, this synergic effect disappears at the 1 % and 1.5 % volume fraction of steel fibres along with carbon and PP fibres. SCHFRC mixes perform better than SCPHFRC mixes at the 1 % and 1.5 % volume fraction of steel fibres.
- Mono CFRC mixes performed poorly with respect to impact load. SCHFRC and SCPHFRC specimens resisted high impact loads prior to complete failure. The specimens with steel-carbon-PP hybrid fibres exhibited the highest impact resistance and the maximum percentage of increase in the post crack resistance of about 69.8 % in the S3C1P1 mix, compared to the control concrete at 28 days. In the S3C1P1 mix, the energy required to produce the first crack increased by 5.82 times and the energy required for complete failure increased by 9.84 times, compared to the control concrete at 28 days. These results reveal that the fibre-hybridization enhances the performance of concrete against impact, and also increases the post cracking resistance compared to the mono fibre system. The incorporation of SCMs blended cement concrete with hybrid fibres not only enhances mechanical properties of concrete but it is also favourable to the economic and environmental aspects of the construction industry.

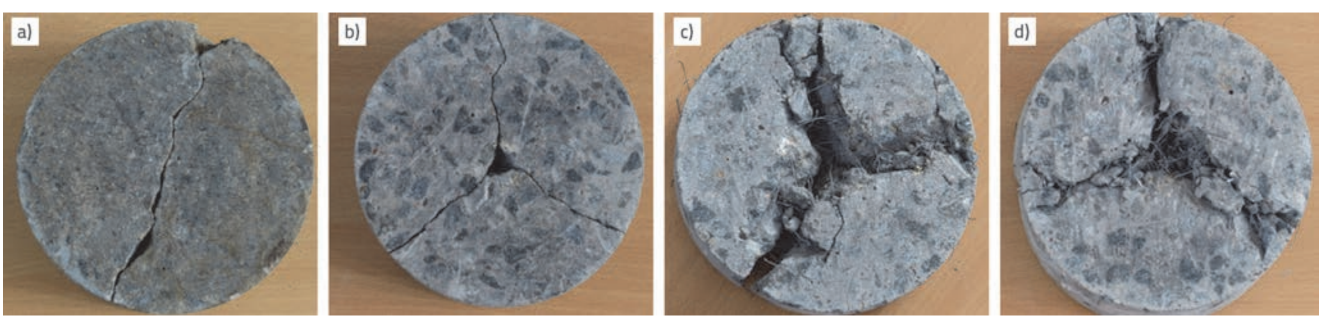


**Figure 8. Failure pattern of specimens: a) Control specimen; b) CFRC; c) SCHFRC; d) SCPHFRC.**

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