

# Effect of fiber hybridization on energy absorption and synergy in concrete

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**ABSTRACT** In the present study, steel and polypropylene (PP) fibers have been utilized with the intent of obtaining hybrid fiber-reinforced concrete (HFRC) with desirable mechanical properties. An attempt has been made to scrutinize the properties of HFRC with the main concentration being on energy absorption characteristics of concrete and the efficacy of fiber hybridization in producing synergy. Accordingly, a total of 180 specimens, representing 20 different mixtures have been cast and evaluated through compressive, split tensile, and flexural tests. The relevant flexural toughness of the specimens was calculated using ASTM C1018, ASTM C1609, JSCE, and PCS methods, and the effectiveness of these methods was evaluated based on the experimental results. It was observed that steel fibers are more effective in the improvement of flexural toughness in the presence of PP fibers. Furthermore, synergy associated with the combination of fibers at different stages of deflection of the beam specimens was observed and analyzed.

**KEYWORDS** hybrid fiber-reinforced concrete, synergy, toughness, steel fibers, polypropylene fibers

## 1 Introduction

Having a low tensile strength and strain capacity, concrete is a material with brittle characteristics. It is possible to achieve a composite with superior mechanical properties using hybrid fibers as the reinforcement [1,2]. Experimental studies show that incorporation of different types of fibers in concrete contributes toward the enhancement of ductility, split tensile strength, flexural strength, resistance to cracking, and most significantly toughness of concrete [3–9]. Synergy can be observed in hybrid fiber-reinforced concrete (HFRC) providing that two or more types of fibers are combined appropriately [10]. In a concrete mixture containing at least two types of fibers, cracking can be addressed at multiple scales using fibers of different sizes. In fact, micro-fibers could control the development of micro-cracks and delay their coalescence into macro-cracks, while macro-fibers are utilized to delay the propagation of macro-cracks, and therefore the concrete demonstrates greater strength and resistance to cracking compared to a mono-fiber-reinforced concrete [11,12].

To achieve a desirable response, different types of fibers

varying in size, function, and constitutive response should be utilized [13]. Ganesan et al. [14] showed that tension stiffening effect and resistance to cracking of concrete is enhanced by the combination of steel and polypropylene (PP) fibers. Vibhuti and Radhakrishna [15] reported that the simultaneous incorporation of steel and PP fibers in concrete improves the compressive strength marginally. On the other hand, hybridization significantly improves split tensile and flexural strength. Rashiddadash et al. [16] tested HFRC specimens by maintaining the total volume content of fibers at 1%. Based on their results, HFRC with 0.75% of steel fibers and 0.25% of PP fibers has higher toughness indices, modulus of rupture and impact resistance than other hybrid composites and steel fiber composites which can be attributed to the synergy produced by incorporation of two types of fibers. Hsieh et al. [17] reported that the hybridization of monofilament and staple PP fibers results in composites with higher compressive, split-tensile and flexural strength in comparison to a single-fiber-reinforced concrete. Banthia and Sheng [18] showed that carbon fiber-reinforced concrete has higher toughness while steel fiber-reinforced concrete benefits from a higher tensile strength. Mechanical properties of hybrid composites based on both carbon

and steel fibers are placed somewhere between those of the equivalent single-fiber composites. Substitution of a proportion of large diameter fibers with those having smaller diameter can improve strain hardening, multiple cracking behavior, and toughness [19,20]. Libre et al. [21] investigated the incorporation of hybrid fibers (steel fibers and fibrillated PP fibers) in lightweight aggregate concrete made with natural pumice. They found that the addition of fibers in hybrid form can significantly enhance the split tensile and flexural strength of concrete made with natural pumice.

Huang et al. [22] found that using hybrid fibers (steel and PP fibers) in reinforced concrete columns could result in enhanced seismic capacity. Caggiano et al. [23] pointed out that recycled fibers with adequate geometrical characteristics can be an appropriate replacement for industrial fibers resulting in HFRC composites with the same mechanical properties. Banyhussan et al. [24] explored whether the development of deflection-hardening concrete mixtures using different types of fibers and a maximal amount of coarse aggregates is viable. Dawood and Hamad [25] investigated the influence of combination of glass and PP fibers on the flexural toughness of high-performance lightweight foamed concrete. Jalsutram et al. [26] studied how the mechanical properties of fiber-reinforced concrete are influenced by varying the volume fraction of chopped basalt fibers. Tian et al. [27] have provided a comprehensive review of recent science and developments regarding natural fiber-reinforced concrete. It is known that HFRC is promising and has been investigated in several studies, yet there is need for more extensive researches to further the development of the essential science for their optimization.

The present study has been conducted to study different aspects of HFRC with the concentration being on the energy absorption capacity of the HFRC mixtures and also to obtain a mixture based on an optimum combination of steel and PP fibers in which initiation and propagation of both micro-cracks and macro-cracks are addressed. A thorough comparison through experimental results is carried out between toughness indices of HFRC beams calculated based on ASTM C1018 [28], ASTM C1609 [29], and JSCE [30] standards and Post Crack Strength (PCS) method [31]. Furthermore, the synergy produced in HFRC composites by replacing a proportion of steel fibers with PP fibers in concrete was investigated.

## 2 Experimental program

In the present study, steel fibers at volume contents of 0.25%, 0.5%, 0.75%, 1% and PP fibers at volume contents of 0.2%, 0.4%, 0.6%, were combined to form 20 various mixtures. Different combinations of fibers result in composites with different mechanical properties. For example, Bajaj et al. [32] found that a combination of

50% steel fibers and 50% PP fibers is effective in contributing to both reductions of variability and flexural fatigue performance, while a combination of 25% steel fibers and 75% PP fibers is the most efficient way for reduction of variability in the distribution of fatigue life. A total of 180 concrete specimens were cast on which compressive strength, split strength, and flexural strength tests were carried out. Following the analysis of the flexural strength tests and by means of load-deformation diagrams, the flexural toughness of specimens was assessed.

### 2.1 Materials used

The experimental program was carried out using ASTM C150 [33] type II Portland cement. Silica fume was also used as a mineral admixture. Coarse aggregates with a maximum size of 12 mm and local natural sand with a specific gravity of 2.66 g/cm<sup>3</sup> were used. Steel fibers adopted in this study are of the hooked end type, having an aspect ratio of 62.5 with physical properties presented in Table 1, and staple PP fibers whose physical properties are given in Table 2 were used. PP fibers were utilized because of their small length and ability to improve flexural toughness at micro-scale crack opening displacements [13]. Moreover, utilization of micro-fibers results in a reduction of shrinkage in the hydrating cement paste [34]. On the other hand, steel fibers were chosen because of their great ability in modifying the post-cracking response of concrete [35].

**Table 1** Physical properties of steel fibers

| parameter        | value | unit              |
|------------------|-------|-------------------|
| density          | 7.85  | g/cm <sup>3</sup> |
| tensile strength | 809   | MPa               |
| length           | 50    | mm                |
| diameter         | 0.8   | mm                |
| aspect ratio     | 62.5  | –                 |

**Table 2** Physical properties of PP fibers

| parameter        | value | unit              |
|------------------|-------|-------------------|
| density          | 0.91  | g/cm <sup>3</sup> |
| elongation       | 80    | %                 |
| tensile strength | 345   | MPa               |
| length           | 12    | mm                |
| diameter         | 35    | microns           |

### 2.2 Mixture proportion and labeling specimens

Mixture proportion utilized in all the specimens for the main test program is given in Table 3. To maintain the workability, slight modifications were applied to the superplasticizer dosage when fibers were added. In the

**Table 3** Mixture proportion for main test program

| cement (kg/m <sup>3</sup> ) | water (kg/m <sup>3</sup> ) | coarse aggregate (kg/m <sup>3</sup> ) | fine aggregate (kg/m <sup>3</sup> ) | silica fume (kg/m <sup>3</sup> ) | super plasticizer (kg/m <sup>3</sup> ) |
|-----------------------------|----------------------------|---------------------------------------|-------------------------------------|----------------------------------|--|
| 400                         | 170                        | 650                                   | 1175                                | 20                               | 2.5                                    |

mixing process, first, the sand, coarse aggregate, cement, and steel fibers were dry mixed for one minute. Afterward, half of the water was added to the mixture and the mixing continued for two minutes. The second half of water with the dissolved superplasticizer and the PP fibers were added and mixed for two more minutes.

In labeling the specimens, P is the symbol of PP fibers and S symbolizes steel fibers, while the number mentioned after each letter represents the volume content of the fiber. For instance, mixture P0.25S0.75 contains 0.2% of PP fibers and 0.75% of steel fibers.

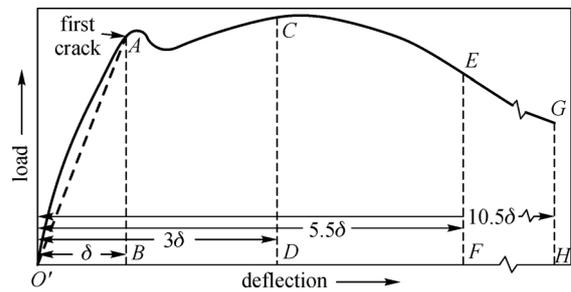
### 2.3 Test methods

Compressive strength was determined in accordance with BS EN 12390-3:2009 [36] test method. For this purpose, cube specimens of dimensions 150 mm×150 mm×150 mm were cast. As applied to all test specimens, following a 28-day period of curing in the water tank, the specimens were tested under a 2000 kN compression testing machine. To perform the split tensile test, cylinder specimens with a diameter of 150 mm and length of 300 mm were cast. This was according to the requirements of ASTM C496 [37] test method. The third-point flexural test was carried out on the specimens with cross-sectional dimensions of 100 mm×100 mm and a length of 500 mm by means of a hydraulic jack while the mid-span displacement was measured using an LVDT, and the applied load was measured using a Load Cell. In accordance with ASTM C1609, the supports were spaced at a distance of 300 mm, while the two loading points were spaced at 100 mm. The test was not terminated until long after the first crack appeared owing to the fact that the specimens containing fibers showed considerable resistance after the peak load, and it was needed to observe the crack propagation in the specimens.

There are a few methods to evaluate the flexural toughness of concrete beams, all of which rely on proposing toughness indices indicating the ability of the specimens in absorbing energy. In this research, ASTM C1018, ASTM C1609, JSCE, and PCS methods were applied to determine the flexural toughness of HFRC concrete beams. Based on previous studies, ASTM C1018 and JSCE methods suffer from a number of deficiencies [31,38,39]. Accordingly, an attempt has been made in the current study to compare the toughness indices calculated by all the aforementioned methods.

To determine the toughness indices by ASTM C1018 method, the first crack deflection is determined and the area under the load-deflection curve up to the first crack

deflection is calculated. Toughness indices of  $I_5$ ,  $I_{10}$ , and  $I_{20}$  are reported by dividing the areas up to 3, 5.5, and 10.5 times the first-crack deflection by the area up to first crack, respectively. The load-deflection and first crack point are shown in Fig. 1.



**Fig. 1** Proposed method by ASTM C1018 to determine flexural toughness.

Toughness indices are calculated using Eq. (1) in accordance with ASTM C1609, where  $T_{150}^D$  is the total area under the load-deflection curve up to a deflection of  $\frac{1}{150}$  of the span length,  $f_1$  is the flexural strength of specimen,  $b$  is the width of specimen, and  $d$  is the depth of specimen.

$$R_{T,150}^D = \frac{150T_{150}^D}{f_1bd^2}. \quad (1)$$

Based on JSCE method, toughness indices are calculated using Eq. (2), where  $\bar{\sigma}_b$  is the flexural toughness factor,  $T_b$  is flexural toughness (determined by calculating the area under load-deflection curve up to  $\delta_{tb}$ ), and  $\delta_{tb}$  is deflection equal to  $L/150$  of the span.

$$\bar{\sigma}_b = \frac{T_b}{\delta_{tb}} \cdot \frac{1}{bh^2}. \quad (2)$$

As illustrated in Fig. 2, the load-deflection curve is divided into two regions in PCS method. PCS is determined for different fraction values of  $L/M$  using Eq. (3), where  $b$  and  $h$  are cross-sectional dimensions,  $L$  is the length of the beam, and  $M$  is a number ranging from a minimum of 150 to a maximum of 3000. As shown in Fig. 2,  $\delta_{\text{peak}}$  is the first-crack deflection.

$$PCS_m = \frac{(E_{\text{post},m})L}{\left(\frac{L}{M} - \delta_{\text{peak}}\right)bh^2}. \quad (3)$$

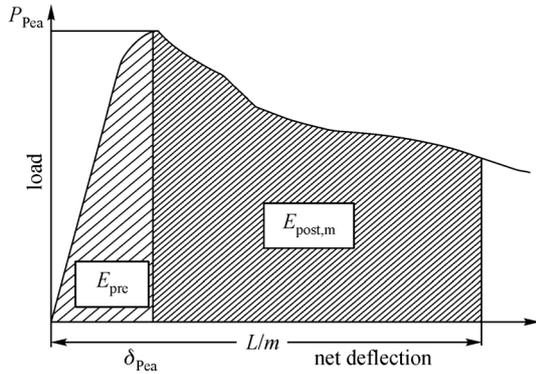


Fig. 2 Proposed method by Banthia and Trottier [31] that divides the load-deflection curve into 2 regions.

### 3 Results

Test results for compressive, split tensile, flexural strength, and first-crack deflection are summarized in Table 4 and categorized into 6 groups for better comparison of the mixtures with similar properties. The first group only contains the control mixture and the second one contains

mono-PP fiber composites. In other groups, each containing 4 different mixtures, steel fibers volume gradually increases from 0.25% to a maximum of 1% while the PP fibers remain constant. Each strength value reported in Table 4 is the average of 3 similar specimens for a specific mixture. The coefficients of variation for compressive and tensile strength test of the specimens were kept under 5% and for the flexural strength test of the specimens was less than 8%.

#### 3.1 Compressive strength and split tensile strength

A minor change is observed in the compressive strength of HFRC specimens in comparison to the control mixture. This result is supported by previous researches available in Refs. [25,40]. As presented in Table 4, the compressive strength ranged from 39.57 MPa to a maximum of 46.84 MPa produced by the mixture containing 1% of steel fibers and 0.4% of PP fibers. In group 2, as the fiber content increases from 0.2% to 0.4%, the compressive strength increases. However, the compressive strength decreases, as the volume content of PP fibers reaches 0.6%. Notice that the average of compressive strength for mixtures in group 5 (specimens with 0.4% of PP fiber) is higher than that of groups 4 and 6 (specimens with 0.2% and 0.6% of PP

Table 4 Test results for compressive, split tensile, and flexural strengths

| group | mixture   | compressive strength (MPa) | average strength of the group* (MPa) | split tensile strength (MPa) | average strength of the group (MPa) | flexural strength (MPa) | average strength of the group (MPa) | first-crack deflection (mm) |
|-------|-----------|----------------------------|--------------------------------------|------------------------------|-------------------------------------|-------------------------|-------------------------------------|-----------------------------|
| 1     | P0S0      | 39.57                      | 39.57                                | 3.84                         | 3.84                                | 4.20                    | 4.20                                | 0.25                        |
| 2     | P0.2S0    | 41.91                      | 42.56                                | 4.24                         | 4.25                                | 4.92                    | 5.09                                | 0.28                        |
|       | P0.4S0    | 43.80                      |                                      | 4.45                         |                                     | 5.22                    |                                     |                             |
|       | P0.6S0    | 41.97                      |                                      | 4.08                         |                                     | 4.96                    |                                     |                             |
|       | P0S0.25   | 42.44                      |                                      | 4.39                         |                                     | 5.04                    |                                     |                             |
| 3     | P0S0.5    | 44.55                      | 44.23                                | 4.44                         | 4.50                                | 5.07                    | 5.23                                | 0.26                        |
|       | P0S0.75   | 44.95                      |                                      | 4.65                         |                                     | 5.40                    |                                     |                             |
|       | P0S1      | 45.50                      |                                      | 4.60                         |                                     | 5.43                    |                                     |                             |
|       | P0.2S0.25 | 44.83                      |                                      | 4.45                         |                                     | 5.10                    |                                     |                             |
| 4     | P0.2S0.5  | 45.73                      | 45.20                                | 4.58                         | 4.77                                | 5.12                    | 5.36                                | 0.30                        |
|       | P0.2S0.75 | 45.75                      |                                      | 4.72                         |                                     | 5.48                    |                                     |                             |
|       | P0.2S1    | 44.48                      |                                      | 5.33                         |                                     | 5.76                    |                                     |                             |
|       | P0.4S0.25 | 44.20                      |                                      | 4.45                         |                                     | 5.72                    |                                     |                             |
| 5     | P0.4S0.5  | 46.66                      | 46.23                                | 5.07                         | 5.06                                | 5.83                    | 6.20                                | 0.29                        |
|       | P0.4S0.75 | 45.84                      |                                      | 4.90                         |                                     | 6.14                    |                                     |                             |
|       | P0.4S1    | 46.84                      |                                      | 5.85                         |                                     | 7.12                    |                                     |                             |
|       | P0.6S0.25 | 43.40                      |                                      | 4.42                         |                                     | 5.00                    |                                     |                             |
| 6     | P0.6S0.5  | 46.35                      | 43.87                                | 5.16                         | 4.91                                | 5.26                    | 5.53                                | 0.26                        |
|       | P0.6S0.75 | 43.34                      |                                      | 5.02                         |                                     | 5.58                    |                                     |                             |
|       | P0.6S1    | 42.40                      |                                      | 5.07                         |                                     | 6.30                    |                                     |                             |
|       |           |                            |                                      |                              |                                     |                         |                                     |                             |

\*Note: The average of the strength of all the mixtures in the group.

fiber). It appears that 0.4% of PP fibers is the optimum fiber content for enhancing the compressive strength both in the presence and absence of steel fibers.

As expected, the addition of fibers leads to the significant enhancement of split tensile strength, especially in hybrid form. The tensile strength of mixtures ranged from 3.84 to 5.85 MPa, with the hybrid fiber-reinforced mixtures yielding the highest tensile strength, increasing it by 52% compared to the control mixture. As illustrated in Table 4, it can be seen in all the groups that the degree of enhancement relies on fiber volume content. Comparing mixtures P0.2S0, P0.4S0, and P0.6S0, and also comparing the average strength of groups 4–6, shows that the mixtures containing 0.4% of PP fibers (both in the presence and absence of steel fibers) have the highest split tensile strength. This can be explained by lower compaction of mixtures containing high dosages of PP fibers. As the amount of PP fibers increases, compaction process becomes less efficient and the number of air voids in concrete increases. This is why the mixtures containing 0.6% of PP fibers demonstrated inferior tensile and compressive strength relative to the mixtures containing 0.4% of PP fibers.

Comparing the average tensile strength of groups 2 and 3 shows that the addition of steel fibers is more effective than PP fibers due to the greater length and modulus of elasticity of steel fibers. Since the tensile strength of steel fiber-reinforced mixtures is higher than that of PP fiber-reinforced mixtures, it is expected to achieve a composite with lower tensile strength when a portion of steel fibers is replaced with PP fibers. On the contrary, the synergic effect of fibers in hybrid mixtures results in higher tensile strength. In fact, synergy can be observed in many cases when comparing the hybrid mixtures to steel fiber mixtures with the same total fiber content. A comparison between mixtures P0.2S0.75 and P0S1 is a clear evidence of synergy because at the same total fiber volume content, mixture P0.2S0.75 has higher split tensile strength. Additionally, notice the superior tensile capacity of mixture P0.4S0.5 (a hybrid composite) over mixture P0S1 in which steel fibers are used individually. In a well-designed HFRC composite, the response is not the result of separate fiber contributions, but rather the characteristics of the resulting material outperforms those of the corresponding mono-fiber composites [41]. This is due to the fact that PP has great stress redistribution ability in lower deflections, and steel fibers with greater length and modulus of elasticity help in the distribution of stress at higher deflections and also restrain the propagation of macro-cracks.

### 3.2 Flexural strength

When compared to split tensile and compressive strength, it appears that the addition of hybrid fibers has the greatest effect on the flexural capacity of concrete. As observed in

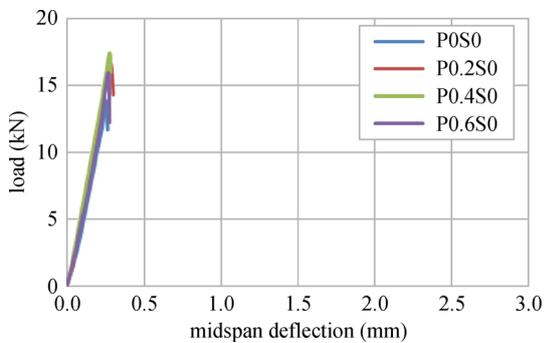
Table 4, the addition of fibers in hybrid form results in an improvement of flexural strength up to 70% relative to the control mixture. Results show that by increasing the content of fibers, the improvement of flexural strength continues. The bridging action developed by PP fibers across the micro-cracks improves the first-crack strength, while the behavior of post-crack zone is improved by utilization of steel fibers. This means that an optimized combination of steel and PP fibers, so that fracture is restrained at multiple scales, enhances both first-crack strength and post-peak response of concrete.

A comparison between mixtures P0S0.5 (with a flexural strength of 5.07 MPa) and P0.2S0.25 (with a flexural strength of 5.1 MPa) shows the positive synergy of fiber hybridization. Similar to split tensile strength, replacing a proportion of steel fibers with PP fibers leads to the improvement of flexural strength. The enhanced bond-slip properties between steel fibers and their surrounding matrix, which is reinforced with PP fibers, leads to producing synergy in hybrid mixtures. Comparing mixtures P0S1 and P0.2S0.75, and also comparing mixtures P0S0.75 and P0.4S0.25 shows that with a lower total fiber content, the mixtures based on hybrid fibers demonstrated higher flexural strength in comparison to the mixtures containing steel fiber. Comparing mixtures P0.2S1 (with a flexural strength of 5.76 MPa) and P0.4S0.75 (with a flexural strength of 6.14 MPa) indicate that some combinations of fibers perform better in terms of producing synergy. In this case, the specimen with a greater portion of steel fibers produces higher flexural strength. In contrast, as it was previously stated, using 25% of steel fibers and 75% of PP fibers is the best combination for decreasing the variability in the distribution of results.

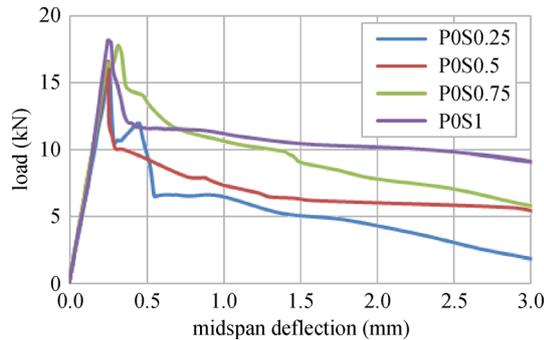
Finally, by comparing the average strength of groups 4–6 in Table 4 it appears that steel fibers have a superior performance in the presence of 0.4% of PP fibers. It can be observed that the flexural strength of mixtures containing 0.2%, 0.4%, and 0.6% of PP fibers is equal to 5.34, 6.2, and 5.53 MPa, respectively. It is to be noted that utilizing fibers can provide flexibility in the constitutive properties of concrete, especially beneficial for a targeted concrete design satisfying a specific need. For instance, steel fibers can be utilized in a concrete mixture with low flexural strength but other attractive characteristics. This way, a composite that benefits from an acceptable flexural strength with the desirable characteristics of the base matrix can be achieved.

Load-deflection curves were plotted using the acquired data from the flexural test in order to evaluate the flexural response of all the mixtures. Figures 3 and 4 demonstrate the load-deflection curves of mixtures containing PP and steel fibers in an individual form, respectively. Figures 5–7 present mixtures based on hybrid fiber reinforcement in which PP fiber content is maintained constant and steel fiber content varies from 0.25% to 1%. Comparing the load-deflection curves of the specimens shows that the

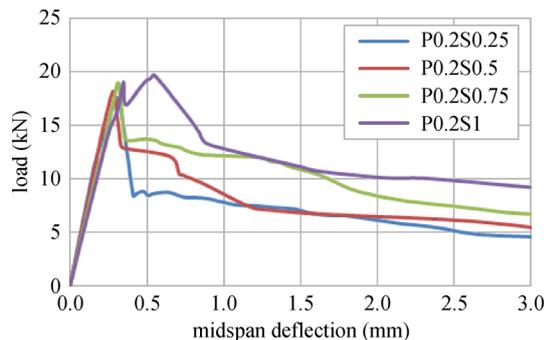
main role played by the fibers occurs in the post-cracking area in which the fibers help to the load redistribution. This is supported by previous researches [40–42].



**Fig. 3** Load-deflection curve of mixtures P0S0, P0.2S0, P0.4S0, and P0.6S0.

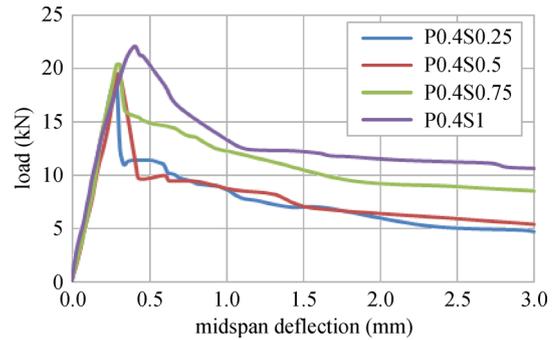


**Fig. 4** Load-deflection curve of mixtures P0S0.25, P0S0.5, P0S0.75, and P0S1.

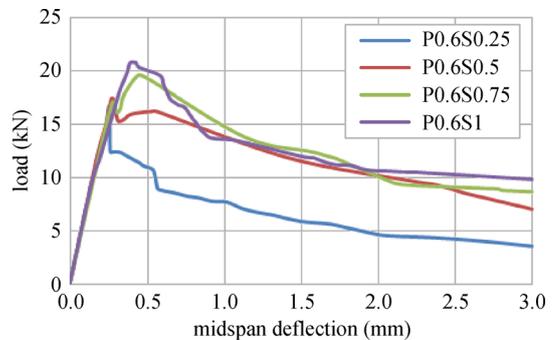


**Fig. 5** Load-deflection curve of mixtures P0.2S0.25, P0.2S0.5, P0.2S0.75, and P0.2S1.

As shown in Fig. 3, there is a sudden decrease in the flexural capacity of mixtures containing only PP fibers since they cannot delay the propagation of macro-cracks, but the ultimate load carrying capacity increases due to the ability of PP fibers in arresting micro-cracks and therefore delaying the failure. The PP fibers are functional at bridging across small cracks and soon experienced pullout since they cannot limit larger cracks and strains. It should



**Fig. 6** Load-deflection curve of mixtures P0.4S0.25, P0.4S0.5, P0.4S0.75, and P0.4S1.



**Fig. 7** Load-deflection curve of mixtures P0.6S0.25, P0.6S0.5, P0.6S0.75, and P0.6S1.

be reminded that fiber pullout is one of the main energy absorption mechanisms in fiber-reinforced composites [43]. According to Fig. 4, as the volume content of steel fibers increases, a clear improvement in the load carrying capacity of mixtures is observed. In fact, a less softening behavior in the post-peak zone characterizes the specimens having a higher amount of steel fibers. The retention of stiffness and superior flexural response demonstrated in specimen P0S1 (compared to the other mixtures in Fig. 4) is the result of a stronger network of fibers bridging across more cracks and the conservation of steel fibers to concrete bond in this specimen.

Figures 5–7 similarly compare the flexural response of composites in hybrid form. In this case, as the steel fiber content increases, load carrying capacity, especially after peak load, is boosted. In contrast, prior to the peak load, the flexural capacity of different mixtures is almost the same. Notice that the specimens with lower fiber content have a steeper post-peak curve.

Following the flexural test, the tension surface of the specimens was inspected for characterizing the state of cracking. In case of the control and PP fiber-reinforced specimens, the specimens suddenly broke into two pieces after reaching the peak load. In the case of steel and hybrid fiber-reinforced specimens, multiple cracking was observed due to fiber-bridging action before reaching the

peak load (presented in Fig. 8). This is in accordance with previous researches stating that a fiber-reinforced composite can provide post-cracking tensile strength higher than the corresponding matrix [44,45].



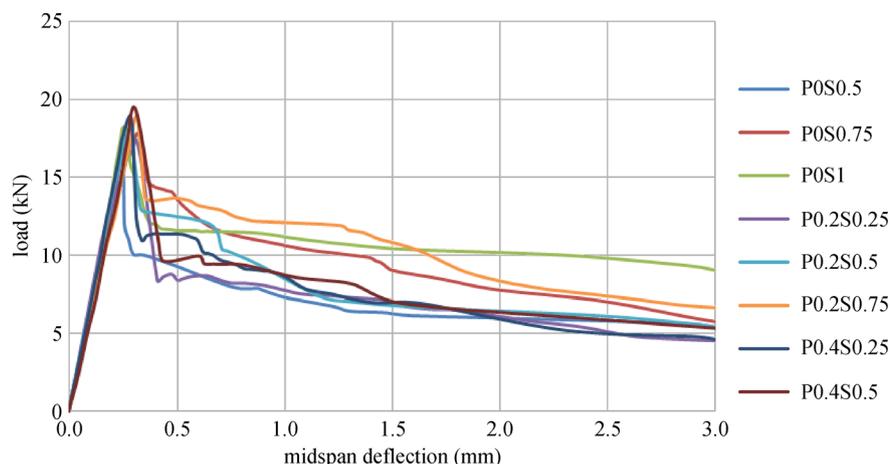
**Fig. 8** Failure in flexural test.

For further examination of the flexural behavior of the specimens, hybrid mixtures are presented in Figs. 9 (presenting mixtures with total volume content of 1% and less) and 10 (presenting mixtures with total volume content of 1% and higher) to compare the load-deflection curves of mixtures with the same total fiber content. As can be seen in Fig. 9, generally, the mixtures with a higher total fiber content demonstrate better flexural performance. On the other hand, the fiber type and content can play a major role in regard to the flexural behavior of the specimens. Mixture P0.2S0.75 has a higher load carrying capacity at deflections of less than 1.5 mm compared to mixture P0S1 (both mixtures have almost the same fiber content). This is a clear sign of synergy because the former containing both

PP and steel fibers outperforms the latter made only with steel fibers. In fact, the slope of the early stages of the softening branch is greater for the mixture with higher content of steel fibers. This can be attributed to a more delayed activation of steel fibers relative to the PP fibers because there is a lower number of macro-fibers corresponding to the equal volume of micro-fibers in a particular zone. Since steel fibers are activated later, PP fibers are the only mechanism for abating cracks at early stages of cracking. Therefore, mixtures containing higher dosages of PP fibers demonstrate superior behavior in the early post-peak stages. Positive synergy can also be observed at low deflections in mixture P0.2S0.25, with the control mixture being P0S0.5. Examination of Fig. 10 also indicates that PP fibers have a great effect on the energy-absorption capacity of concrete beams at low deflections. Mixtures P0.4S0.75 and P0.6S0.75 showed a higher load-carrying capacity at deflections less than 1.5 mm compared to mixture P0S1 because of the presence of PP fibers, while the load-carrying capacity of the latter is greater at higher deflections. Similarly, mixture P0.6S0.75 has a higher load-carrying capacity at deflections below 2 mm compared to mixture P0.4S1 because of its higher PP fiber content. In all cases, after the deflection of 2 mm, there is no sign of synergy and mixtures with higher content of steel fibers offer better response even compared to hybrid fiber mixtures. It should be reminded that a specific type of fiber only has the ability to produce reinforcement at a specific level and address the crack growth within a specific range of strains.

### 3.3 Toughness

In this section, toughness indices determined by ASTM C1018, ASTM C1609, JSCE, and PCS methods are reported and analyzed. Tables 5–8 are provided with the intent of assessing the effectiveness of steel fibers. In each table, steel fiber content ranges from 0.25% to 1% while



**Fig. 9** Comparison of mixtures with a total fiber content of 1% and less.

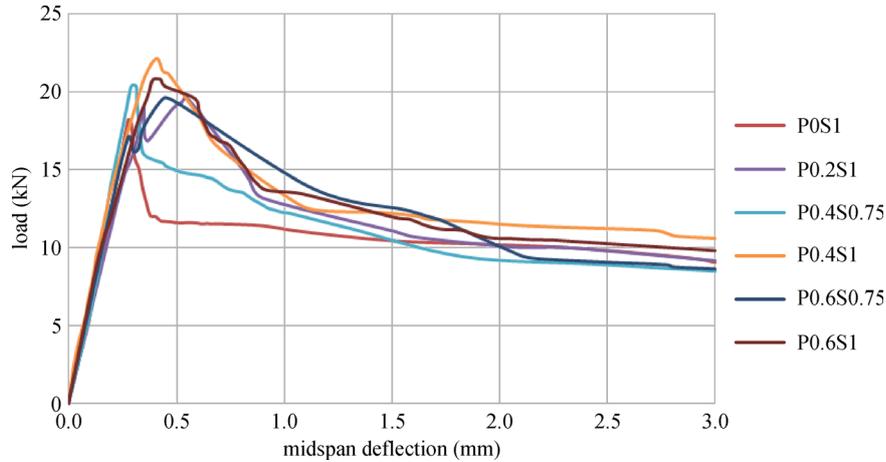


Fig. 10 Comparison of mixtures with a total fiber content of 1% and higher.

Table 5 Toughness indices of mixtures P0S0.25, P0S0.5, P0S0.75, and P0S1

| mixture | test method |          |          |                  |         |         |         |               |
|---------|-------------|----------|----------|------------------|---------|---------|---------|---------------|
|         | ASTM C1018  |          |          | JSCE             | PCS     |         |         | ASTM C1609    |
|         | $I_5$       | $I_{10}$ | $I_{20}$ | $\bar{\sigma}_b$ | $L/450$ | $L/300$ | $L/150$ | $R_{T,150}^D$ |
| P0S0.25 | 3.35        | 5.18     | 6.84     | 1.90             | 2.83    | 2.42    | 2.12    | 14.24         |
| P0S0.5  | 4.85        | 7.61     | 13.15    | 2.35             | 2.68    | 3.10    | 2.83    | 18.50         |
| P0S0.75 | 3.66        | 5.78     | 7.93     | 3.00             | 3.58    | 3.97    | 3.58    | 19.40         |
| P0S1    | 4.43        | 9.27     | 15.54    | 3.10             | 3.80    | 4.10    | 3.20    | 19.90         |

Table 6 Toughness indices of mixtures P0.2S0.25, P0.2S0.5, P0.2S0.75 and P0.2S1

| mixture   | test method |          |          |                  |         |         |         |               |
|-----------|-------------|----------|----------|------------------|---------|---------|---------|---------------|
|           | ASTM C1018  |          |          | JSCE             | PCS     |         |         | ASTM C1609    |
|           | $I_5$       | $I_{10}$ | $I_{20}$ | $\bar{\sigma}_b$ | $L/450$ | $L/300$ | $L/150$ | $R_{T,150}^D$ |
| P0.2S0.25 | 3.10        | 4.95     | 5.72     | 2.40             | 3.22    | 3.10    | 2.40    | 16.10         |
| P0.2S0.5  | 4.43        | 7.00     | 9.66     | 2.64             | 4.00    | 3.63    | 2.73    | 17.18         |
| P0.2S0.75 | 4.26        | 7.17     | 9.62     | 3.38             | 4.40    | 3.95    | 3.65    | 19.55         |
| P0.2S1    | 5.04        | 7.58     | 10.97    | 4.12             | 4.45    | 6.31    | 4.93    | 23.03         |

Table 7 Toughness indices of mixtures P0.4S0.25, P0.4S0.5, P0.4S0.75 and P0.4S1

| mixture   | test method |          |          |                  |         |         |         |               |
|-----------|-------------|----------|----------|------------------|---------|---------|---------|---------------|
|           | ASTM C1018  |          |          | JSCE             | PCS     |         |         | ASTM C1609    |
|           | $I_5$       | $I_{10}$ | $I_{20}$ | $\bar{\sigma}_b$ | $L/450$ | $L/300$ | $L/150$ | $R_{T,150}^D$ |
| P0.4S0.25 | 3.06        | 4.81     | 6.60     | 2.50             | 3.37    | 3.10    | 2.38    | 14.11         |
| P0.4S0.5  | 3.54        | 5.28     | 6.77     | 2.40             | 3.75    | 3.10    | 2.47    | 14.94         |
| P0.4S0.75 | 4.44        | 7.18     | 13.95    | 3.63             | 4.60    | 4.40    | 4.70    | 18.04         |
| P0.4S1    | 3.00        | 4.54     | 6.62     | 4.30             | 6.74    | 6.00    | 4.54    | 21.32         |

the PP fiber content remains constant. It should be reminded that the all indices reported in these tables are the average of the results of three specimens. Comparing the toughness indices of 4 mixtures in each table based on

the results acquired from JSCE, PCS, and ASTM C1609 methods shows that there is an increasing trend in the values of toughness indices as the volume content of steel fibers increases. In most cases, there is a dramatic increase

**Table 8** Toughness indices of mixtures P0.6S0.25, P0.6S0.5, P0.6S0.75 and P0.6S1

| mixture   | test method |          |          |                  |         |         |         |               |
|-----------|-------------|----------|----------|------------------|---------|---------|---------|---------------|
|           | ASTM C1018  |          |          | JSCE             | PCS     |         |         | ASTM C1609    |
|           | $I_5$       | $I_{10}$ | $I_{20}$ | $\bar{\sigma}_b$ | $L/450$ | $L/300$ | $L/150$ | $R_{T,150}^D$ |
| P0.6S0.25 | 4.26        | 6.92     | 10.55    | 2.23             | 3.41    | 3.20    | 2.30    | 14.92         |
| P0.6S0.5  | 5.00        | 9.17     | 14.10    | 3.48             | 4.90    | 4.72    | 4.45    | 23.00         |
| P0.6S0.75 | 6.40        | 11.97    | 18.73    | 4.08             | 5.40    | 5.50    | 4.70    | 23.60         |
| P0.6S1    | 3.58        | 5.12     | 6.98     | 3.74             | 6.56    | 5.70    | 3.84    | 21.42         |

in the toughness indices once the steel fiber content changes from 0.25% to 0.5%. Thus, it appears that it is not efficient to use steel fibers less than 0.5% as the reinforcement for concrete.

A comparison between PCS indices of mixtures POS0.75 and P0.2S0.5 and also between PCS indices of mixtures POS1 and P0.2S0.75 shows that the specimens with higher steel fiber content have a higher  $L/150$  index, whereas the specimens with higher PP fiber content has a higher  $L/450$  index. This supports the facts that the PP fibers are more effective at lower deflections, and steel fibers are more effective at higher deflections. At micro-scale, fibers control the initiation of cracks, while at the macro-scale, fibers provide toughness and ductility [20]. The bridging action of fibers is the main reason for the toughening mechanism in the fracture process zone of concrete specimens. This action is controlled by several parameters such as the fiber type and content, the distribution of fibers, fiber pull-out, and the bonding capacity between fibers and matrix.

Comparing the toughness indices of mixtures containing only steel fibers (provided in Table 5) with the hybrid mixtures (provided in Tables 6 and 7) shows that steel fibers are more effective in improvement of flexural toughness in the presence of PP fibers. In the absence of PP fibers, as the volume content of steel fibers increases from 0.25% to 1%, the toughness indices based on JSCE and ASTM C1609 increase up to 63% and 40%, respectively. In the presence of PP fibers, as the content of steel fibers increases from 0.25% to 1%, these indices increase up to 72% and 58%, respectively. This shows that the degree of improvement in toughness is higher when steel fibers are used along with PP fibers which can be attributed to the positive synergy achieved by the simultaneous application of two types of fibers. It is also worth mentioning that as the steel fiber content increase from 0.25% to 1%, the flexural indices increase up to 72%, while the flexural strength of the specimens increases up to 25%. Another way to investigate the synergy is inspection of the response of PP fiber-reinforced mixtures. Mixtures with low content of PP fibers alone show little or no flexural improvement over control mixtures. However, when PP fibers are combined with steel fibers, an improvement is observed in flexural strength of hybrid

mixture over steel fiber-reinforced mixture. PP fibers, which by themselves cannot modify the toughness of concrete, contribute to improvement of toughness in the presence of steel fibers.

As observed in Tables 5–8, indices  $I_5$  and  $I_{10}$  acquired based on ASTM C1018 are incapable of evaluating the flexural toughness of the specimens appropriately. The values of  $I_5$  and  $I_{10}$  increase as the steel fiber content increases from 0.25% (in mixture POS0.25) to 0.5% (in mixture POS0.5) followed by a decline in mixture POS0.75 containing 0.75% of steel fibers. However, comparing the toughness indices acquired from methods other than ASTM C1018 and the observation of the load-deflection curves indicate that the energy absorption capacity of the specimens improves as the steel fiber content increase from 0.5% to 0.75%. Such observations are supported by other researchers [39]. The minor issue with PCS method is that it cannot differentiate between toughness indices at different beam deflections for a given specimen. As can be seen in Tables 5–8, the comparison of toughness indices for a given mixture calculated at deflections of  $L/150$ ,  $L/300$ , and  $L/450$ , shows that the indices do not increase as the deflection increases, in spite of the fact that total energy absorbed by concrete has increased.

To further investigate the effect of PP fibers on the improvement of flexural toughness, Table 9 is provided. The values reported in each row are the average of toughness indices of all mixtures made with the same amount of PP fibers. For instance, the values in the second row are the average of toughness indices of mixtures P0.2S0.25, P0.2S0.5, P0.2S0.75, and P0.2S1. Comparing the results in Table 9 shows the indices calculated based on ASTM C1018 method do not follow a rationale pattern as the fiber content changes meaning that this method cannot describe the effect of PP fibers on the enhancement of flexural toughness. Based on the results of PCS and JSCE methods it can be observed that the energy absorption capacity of concrete beams presented by toughness indices rises as the volume content of PP fibers increases.

Analyzing the PCS indices provided in Table 9 reveals that by adding 0.6% of PP fibers to the mixtures, the  $L/450$  indices describing the specimen toughness at lower deflections increase from 3.21 to 5.06 (57% increase), while the  $L/150$  indices describing the specimen toughness

**Table 9** Toughness indices at a constant steel fiber content

| PP fiber volume content | average of toughness indices of the mixtures containing the same amount of PP fibers |          |          |                  |         |         |         |               |
|-------------------------|--|----------|----------|------------------|---------|---------|---------|---------------|
|                         | ASTM C1018   |          |          | JSCE             | PCS     |         |         | ASTM C1609    |
|                         | $I_5$  | $I_{10}$ | $I_{20}$ | $\bar{\sigma}_b$ | $L/450$ | $L/300$ | $L/150$ | $R_{T,150}^D$ |
| 0                       | 4.07   | 6.96     | 10.86    | 2.65             | 3.21    | 3.39    | 2.93    | 17.76         |
| 0.2                     | 4.20   | 6.67     | 8.99     | 3.15             | 4.01    | 4.24    | 3.42    | 19.71         |
| 0.4                     | 3.51   | 5.45     | 8.48     | 3.20             | 4.61    | 4.15    | 3.52    | 16.87         |
| 0.6                     | 4.81   | 8.30     | 12.59    | 3.50             | 5.06    | 4.78    | 3.82    | 21.23         |

at higher deflections increase from 2.93 to 3.82 (30% increase). This supports previous results on the capability of PP fibers in improving the flexural load capacity at low deflections and shows that PCS method is able to accurately differentiate between the ability of PP fibers in improving the flexural toughness at low and high deflections. Additionally, in contrast to split tensile and flexural strength, increasing the PP fibers from 0.4% to 0.6% results in the enhancement of flexural toughness. This shows the usefulness of PP fibers in improving energy absorption, especially for small deflections since they can lower the stress concentration at the edges of cracks.

Based on the results of this study, it appears that JSCE and PCS methods can accurately evaluate the efficacy of both steel and PP fibers in the enhancement of flexural toughness. ASTM C1609 can also describe the effectiveness of steel fibers appropriately, but in a few cases, the indices calculated based on this method do not change according to the changes of PP fiber content. On the other hand, ASTM C1018 is not able to describe the effect of steel and PP fibers on the improvement of toughness accurately.

#### 4 Conclusions

In this study, steel fibers and PP fibers were combined to form 20 different concrete composites. A total of 180 concrete specimens were cast on which compressive, split tensile, and flexural tests were carried out. Based on the results reported in the present study, the following conclusions can be drawn:

1) In the absence of PP fibers, as the volume content of steel fibers increases from 0.25% to 1%, the toughness indices calculated based on JSCE and ASTM C1609 methods increase up to 63% and 40%, while in the presence of PP fibers, the indices increase up to 72% and 58%, respectively. This reveals that steel fibers are more effective in improvement of flexural toughness in the presence of PP fibers.

2) In all cases in the flexural test, after the deflection of 2 mm there is no sign of synergy, and mixtures with higher content of steel fibers demonstrate better flexural performance even compared to hybrid fiber mixtures. On the

other hand, comparing the mixtures with the same total fiber content shows that hybrid mixtures containing PP and steel fibers showed a higher flexural load capacity at low deflections (less than 1.5 mm) compared to mixtures made only with steel fibers.

3) Adding 0.6% of PP fibers to the mixtures results in increasing the toughness indices calculated at low deflections by 57%, while the indices calculated at higher deflections increase by 30%. This shows that PP fibers have a great effect on the energy-absorption capacity of concrete at lower deflections.

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