European Journal of Environmental and Civil Engineering

Volume 26 Number 3 February 2022

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tece20

An experimental and statistical investigation on the fresh and hardened properties of HFR-SCC: the effect of micro fibre type and fibre hybridization

Mahmut Bassurucu & Kazim Turk

To cite this article: Mahmut Bassurucu & Kazim Turk (2022): An experimental and statistical investigation on the fresh and hardened properties of HFR-SCC: the effect of micro fibre type and fibre hybridization, European Journal of Environmental and Civil Engineering, DOI: 10.1080/19648189.2022.2042396

To link to this article: https://doi.org/10.1080/19648189.2022.2042396

Published online: 24 Feb 2022.

EUROPEAN JOURNAL OF ENVIRONMENTAL AND CIVIL ENGINEERING
https://doi.org/10.1080/19648189.2022.2042396

Taylor & Francis
Taylor & Francis Group

An experimental and statistical investigation on the fresh and hardened properties of HFR-SCC: the effect of micro fibre type and fibre hybridization

Mahmut Bassurucu[a] and Kazim Turk[b]

[a]Department of Construction Technology, Darende Vocational High School, Malatya Turgut Ozal University, Malatya, Turkey; [b]Department of Civil Engineering, Engineering Faculty Inonu University, Malatya, Turkey

ABSTRACT

In this study, experimental and statistical analyses were conducted to reveal the effect of micro steel and/or polypropylene (PP) fibre with macro steel fibre as binary and ternary hybridization on the fresh, mechanical and flexural performance of hybrid fibre reinforced self-compacting concrete (HFR-SCC). For this purpose, some tests were conducted related to fresh and hardened properties. It was seen that PP had negative effect on the fresh properties of HFR-SCC mixtures compared to micro steel fibre. Moreover, multiple linear regression (MLR) was used to estimate the fresh and hardened properties of HFR-SCC as function of the percent of fibres by volume while ANOVA analysis determined the contributions of parameters. It was obtained from statistical analysis that there was a good correlation between experimental results and predicted values with approximately $R^2=0.91$ except for compressive strength. Finally, the use of PP with micro steel fibre as ternary hybridization increased the compressive, splitting, flexural tensile strengths, toughness and ductility of HFR-SCC with 1.1%, 13.2%, 18.8%, 14.9% and 26.3%, respectively, while the inclusion of PP into the mixture as binary hybridization had less positive effect on the hardened properties compared to binary steel fibre reinforced SCC with 0.25% micro steel fibre.

ARTICLE HISTORY
Received 27 September 2021
Accepted 8 February 2022

KEYWORDS
Polypropylene fibre; micro steel fibre; self-compacting concrete; four-point bending test; ANOVA analysis; multiple linear regression

1. Introduction

Although concrete has very important advantages compared to other materials such as steel, wood etc. its low tensile strength is disadvantage under bending loads, especially. However, the use of reinforcing bar in concrete solved these problems except for the detailing of rebars properly and high workforce. Besides, the idea about the inclusion of fibres is quite old to enhance the properties of cementitious materials. Different types of fibres such as steel, polypropylene, glass and carbon are prevalently used to improve the tensile strength, toughness, and ductility properties of concrete. The most important factors affecting the performance of fibre reinforced concrete are their geometric shape (smooth, hooked, twisted, and crimped), aspect ratio, the volume fraction, mechanical properties (tensile strength and stiffness), matrix properties (matrix strength, stiffness and Poisson's ratio) and interfacial properties (adhesion, frictional and mechanical bond) between matrix and fibre (Kim et al., 2008).

The use of fibre reinforced concretes in different structure implementations recently gained popularity, such as the application fields of bridge decks, nuclear power plant and airport runway. Besides, while

CONTACT Mahmut Bassurucu mahmut.bassurucu@ozal.edu.tr Department of Construction Technology, Darende Vocational High School, Malatya Turgut Ozal University, Malatya 44210, Turkey.

single fibre reinforcement improved the mechanical and flexural properties of concrete up to a limited level, hybridization of two or more diverse fibres enhanced the hardened properties of concrete much better due to the synergistic effect (Balcikanli Bankir & Sevim, 2020; Bassurucu & Turk, 2019; Turk et al., 2010, 2019; Turk & Bassurucu, 2021).

The self-compacting concrete (SCC), which was developed in Japan at the end of 1980 by Ozawa et al. (1989) as an innovative concrete type, has many important advantages compared to conventional concrete. Because SCC does not necessitate vibration and consolidates under its own weight into mould. SCC is also described as a special type concrete that has a high flowability without segregation and bleeding. In SCC mixtures, Portland cement is usually replaced with mineral admixtures such as fly ash (FA), silica fume (SF) and natural pozzolan to improve fresh and hardened properties of SCC as well as to decrease its cost (Turgut et al., 2012; Turk, 2012; Turk et al., 2010).

As for literature about fibre reinforced, Aboutair et al. (2020) carried out an experimental study to determine the effect of mineral additions and fibre reinforcement on the micro structural characterization and physico-mechanical properties of high performance fibre concretes. This study highlighted that the microstructure had an important impact on the improvement of physico-mechanical characteristics of concrete. Moreover, Turk et al. (2021) conducted a work to evaluate the influence of a total fibre volume and hybridization on the fresh, mechanical and flexural properties of fibre reinforced self-compacting concrete (FR-SCC). In conclusion, although the fresh properties of HFR-SCC mixtures decreased with the increase in a total volume of fibres, HFR-SCC specimens were displayed the excellent mechanical and flexural performance. In another study, the usability of alpha vegetal fibres replaced by synthetic PP fibre was investigated to produce green concrete with suitable mechanical properties. As a result, it has been revealed that alpha fibre reinforcement can be used to obtain a cheaper, eco-friendly and better concrete compared to PP fibre reinforcement (Khelifa et al., 2018). Moreover, Fallah-Valukolaee and Nematzadeh (2020) examined the influence of pozzolan and fibre reinforcement on the shape of the stress-strain diagram, compressive strength, ultimate strain and toughness index parameters of fibre reinforced high strength concrete. Depending on the results obtained in experimental studies, empirical expressions have been developed for the relevant parameters of the stress-strain diagram of synthetic fibre reinforced concrete. In a different study carried out by Manjunath et al. (2020), in addition to the three by-products procured from the iron and steel industry, different proportions of steel fibres were added to the mixtures to improve the cracking behaviour of concrete under the mechanical loads and high temperatures. In conclusion, it was determined that the self-compacting alkali-activated slag concrete mixtures had a suitable workability properties that conformed to the EFNARC standard and a superior toughness performance. Besides, an experimental study was conducted by Niu et al. (2020), to investigate the effects of axial compression ratio, stirrup ratio and high performance PP fibre reinforcement on the seismic behaviour of lightweight aggregate columns. In their study, it was emphasized that the inclusion of high-performance PP fibres into mixtures had more significant effect than the increased stirrup ratio on the preventing of crack development, ductility and energy absorption capacity of the column specimens.

In the study of Ding et al. (2020), the addition of macro PP and/or steel fibres into concrete were evaluated through topographical analysis method. Finally, the HFR concrete specimens displayed an important enhancement in the toughness of concrete. Besides, Kina et al. (2021) studied the prediction of fresh properties of HFR-SCC mixtures having different combinations of fibres by using extreme learning machine and long short-term memory method. They found that the extreme learning machine method had better estimation ability than the deep learning method. Moreover, Mahapatra and Barai (2018) studied fresh and hardened properties of HFR-SCC specimens with crimped steel fibres and PP fibres together with FA and colloidal nano silica as experimental. Then, the tensile strength of specimens was estimated by using MLR and they found that there was a good correlation between test results and predicted values. Besides, experimental and analytical evaluation were carried out by Thomas and Ananth (2007) to study the effect of inclusion of fibres on the mechanical properties of concrete. The variables were the grades of concrete (normal strength-35 MPa, moderately high strength-65 MPa and high strength concrete-85 MPa) and the volume fractions of fibre (0, 0.5, 1 and 1.5%). Finally, it was found that the developed model estimated the test data with a high accuracy. Balcikanli Bankir and Sevim (2020) studied the effect of the hybridization of different fibre (steel, glass, synthetic and PP), FA, electrical arc furnace slag and binder dosage on the compressive strength, flexural strength, pull out capacity, resonance frequency and abrasion resistance of HFR concrete specimens. The statistical analysis displayed that

Table 1. Chemical compound of pozzolanic cement and FA (%).

Composition	Pozzolanic cement	FA
SiO_2	29	63.04
Al_2O_3	9.5	21.63
Fe_2O_3	5.5	6.77
CaO	41	1.07
MgO	1	–
SO_3	2.86	0.10
K_2O	0.68	–
Na_2O	0.60	–
LOI	–	2.6
Specific gravity	2.95	2.3
Surface area (cm^2/g)	4380	2690

the hybridization of fibres had a positive effect on the flexural strength depend on the fibre type and volume fraction.

This work aimed to underscore the design of HFR-SCC in terms of micro fibre type (PP and micro steel fibre) and different fibre combinations based on the fresh and hardened properties as well as flexural performance as experimental and statistical. Also, ANOVA analyses were carried out to find the contribution of the fibre type to the fresh and hardened properties as well as toughness of the HFR-SCC while counter plot diagrams were drawn to examine the influence of micro fibre type on the properties of binary HFR-SCC.

2. Research significance

In the current studies in the literature on HFR-SCC, according to the knowledge of the authors, the effect of use of different micro fibre type (steel and PP) with macro steel fibre as ternary hybridization on workability, mechanical and flexural performance of HFR-SCC has been limitedly investigated. On the other hand, statistical works on mechanical and flexural properties were performed based on 90 curing days because it was important to give adequate time for the pozzolanic reaction between FA and CH. Also, it should be emphasized that the estimation of mechanical and flexural properties by MLR were especially valid in case of a total of 1.25% fibre volume fraction and maximum 0.25% PP as well as moderately high-strength (approximately 70 MPa) concrete in the mixtures. Because, the fibre volume fractions mentioned above were vital to ensure possibly the workability requirements suggested by EFNARC limits in term of self-compactability. Besides, counter plot diagrams were drawn to determine the effect of micro fibre type (steel, PP) and fibre hybridization on the fresh and hardened properties as well as flexural toughness of binary HFR- SCC.

3. Experimental procedure

3.1. Materials

The materials used in SCC contained pozzolanic cement (CEM IV 32.5 R), FA, coarse aggregate, fine aggregate, macro and micro steel fibre as well as polypropylene fibre, high-range water reduced admixture and municipal water. In all SCC mixtures, pozzolanic cement CEM IV 32.5 R and FA were included as binder materials. The chemical compounds of pozzolanic cement and FA were indicated in Table 1. In the preparation of the SCC mixtures, two different types of aggregates were used: fine aggregate (0–5 mm) and coarse aggregate (5–15 mm). Saturated surface dry situation of fine and coarse aggregates was considered for all SCC mixtures. The specific gravity and the water absorption capacity of the fine aggregate were determined as 2.39 and 2.3% while they were 2.68 and 0.4% for the coarse aggregate, respectively. The gradation curves of sum, fine and coarse aggregate was displayed in Figure 1.

In this study, three type fibres having different shapes and aspect ratios were selected in the production of single and HFR-SCC. The properties of macro and micro steel fibre as well as PP fibre were given in Table 2.

To control the workability of fresh concrete, modified polycarboxylic polymer based high-range water reducer admixture (HRWRA) was used. The amount of pozzolanic cement and FA were kept invariable

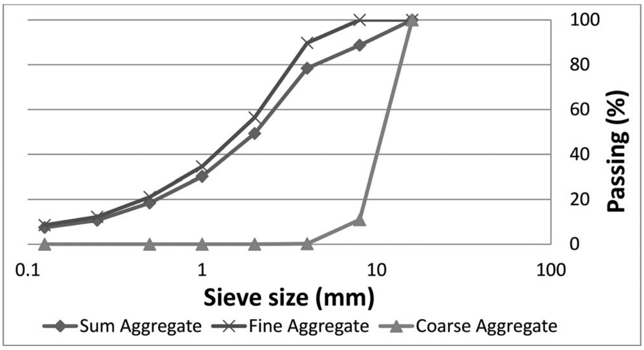
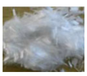


Figure 1. Gradation curves of sum, fine and coarse aggregates.

Table 2. Properties of fibers.

Fiber Type	View	Length (mm)	Diameter (mm)	Aspect Ratio	Tensile Strength (MPa)	Elastic Modulus (GPa)	Density (g/cm^3)
Macro steel		60	0.90	66	Min 1150	210	7.8
Micro steel		13	0.15	87	3000	200	7.2
PP		6	0.025	240	350	–	0.91

while HRWRA content was changed to conform to the EFNARC (2005). Moreover, Malatya city water was used as mixing water.

3.2. Mixture proportions

All SCC mixtures were designed by constant water-binder ratio with 0.28. Three different types of SCC mixture designed were adopted: CONTROL without fibre, single macro steel and hybrid (macro-micro steel fibre, macro steel-PP fibre, macro steel-micro steel and PP) fibre reinforced SCC. The quantities of Pozzolanic cement, FA and water components were 500, 400 and 250 kg/m^3, respectively, for all SCC mixtures. In this study, a total of fibre volume used was changed from 1.0% to 1.25%. The SCC mixture proportions were presented in Table 3. In the labelling of the SCC mixtures, MAC, MIC and PP represent macro, micro and polypropylene fibre, respectively, and the numbers indicate the amount of fibre reinforcement. For example, MAC0.80_MIC0.20_PP0.25 stands for that the SCC mixtures contain 0.80% macro and 0.20% micro steel fibre as well as 0.25% polypropylene fibre. Also, in all SCC mixtures, fine (0–5 mm) and coarse (5–15 mm) aggregates were used 80% and 20% of the sum aggregates, respectively. To obtain the workability limit values according to EFNARC (2005), HRWRA was changed from 0.5 to 1% by binder weight.

The SCC mixtures were prepared using a 50 litre capacity mixer located in the Construction/ Mechanical Laboratory of the Civil Engineering Department of Inonu University. While producing the SCC mixtures, firstly coarse aggregate, fine aggregate, macro fibre and two thirds of water were added and mixed. After that, while the mixer was rotating, micro steel and PP fibres were added gradually into the concrete mixture to ensure uniform distribution and the mixing process continued for a total of 3 minutes. Then, cement, FA and the remaining one-third of the mixing water mixed with HRWRA were included into the mixer and mixing was continued for another 7 minutes. Thus, a total mixing process of 10 minutes was applied to all SCC mixtures.

Table 3. Self-compacting concrete mixtures proportions (kg/m^3).

Mixture Code	Binders		Aggregates		HRWRA	Water	Fiber		
	Cement	FA	(0–5) mm	(5–15) mm			Macro Steel	Micro Steel	PP
CONTROL	500	400	799.32	199.83	4.5	250	–	–	–
MAC1.00	500	400	777.82	194.45	5	250	78.5	–	–
MAC1.25	500	400	773.91	193.48	5	250	98.13	–	–
MAC0.80_MIC0.20	500	400	777.82	194.45	5	250	62.8	14.4	–
MAC1.00_MIC0.25	500	400	771.96	192.99	6	250	78.5	18	–
MAC1.00_PP0.25	500	400	768.05	192.01	8.5	250	78.5	–	2.28
MAC0.80_MIC0.20_PP0.25	500	400	766.1	191.52	9	250	62.8	14.4	2.28

3.3. Test procedures

3.3.1. Workability properties

To provide a suitable workability in self-compacting concrete, excellent flowability, good passing ability and a high deformability were fundamental. For this reason, the slump-flow and J-ring tests were carried out to evaluate the consistency and passing ability of fresh concrete according to the workability limits designated by EFNARC (2002). During the slump-flow tests, the slump-flow diameter and T_{500} values were obtained. It was evaluated to interpret the even flow of fresh concrete without obstruction equipment. Afterwards, the diameter value was gauged in both directions and their average was defined as slump-flow diameter. It was explicit that the higher slump-flow diameter value means excellent flow-ability for SCC. Also, the slump-flow test was performed for the time necessary to reach the diameter value of 500 mm and it was named as T_{500}. It was apparent that the smaller T_{500} value the higher flowability. The difference between the tests of slump-flow and J-ring were the ring apparatus around Abram's cone. Moreover, in the J-ring tests, the average of divergences between the heights of SCC just inside and outside of the ring equipment was considered. Thus, it was obvious that the lower divergences of the heights, the better passing ability of SCC.

3.3.2. Mechanical properties and flexural performance

After determining the workability properties of fresh SCC, it was poured into the molds and kept in it for 1 day. To prevent dehydration, the SCC specimens were wrapped with a nylon sheet and waited at room temperature until removed from the molds. After the SCC specimens were removed from the mold, they were cured in the water for 28 and 90 days and tested to determine the compressive, splitting tensile and flexural tensile strengths. The compressive strength tests were carried out by preparing the three standard cube SCC specimens having the dimension of 100x100x100 mm according to ASTM C39 (ASTM, 2008). To determine splitting tensile strength, three cylinder SCC specimens with the dimension of Ø100x200 mm were tested as per ASTM C496 (ASTM, 2011).

Moreover, the flexural strength of the concrete specimens was conducted by implementing four-point bending test on prismatic SCC specimens having the size of 75x100x400 mm as per ASTM C78 (ASTM, 2002). All the clear span of prismatic beam specimens was 300 mm. Prismatic beam specimens were subjected to the four-point bending using a 300 kN load capacity servo-controlled testing machine with a load rate of 0.003 mm/s. To measure the mid-span deflection, frame equipment was placed to the prismatic SCC specimens through four screws at the support and a Linear Variable Differential Transformer (LVDT) was installed into this frame equipment. The applied vertical load and mid-span deflection values were recorded during the tests by means of a data acquisition system. The schematic of test setup was displayed in Figure 2.

In addition to these, flexural toughness was a vital parameter to assess the contribution of fibres at the post-peak response of fibre reinforced concretes. Due to many difficulties encountered, the ASTM C1018 (ASTM, 1997) standard used in the evaluation of flexural toughness was replaced with ASTM C1609 (ASTM, 2005) standard. Because, many studies (Turk et al., 2020, 2021; Yu et al., 2015) emphasized that it was quite difficult to accurately determine the first crack point at the load vs. mid-span deflection diagram based on ASTM C1018 (ASTM, 1997). It was also stated that this code was insufficient in evaluating the flexural toughness of innovation concretes such as hybrid reinforced concretes (Turk et al., 2021). Therefore, in this study, flexural toughness of FR-SCC having different fibre combinations and micro fibre types of mixtures were evaluated according to ASTM C1609 (ASTM, 2005) and JSCE (JSCE, 2005)

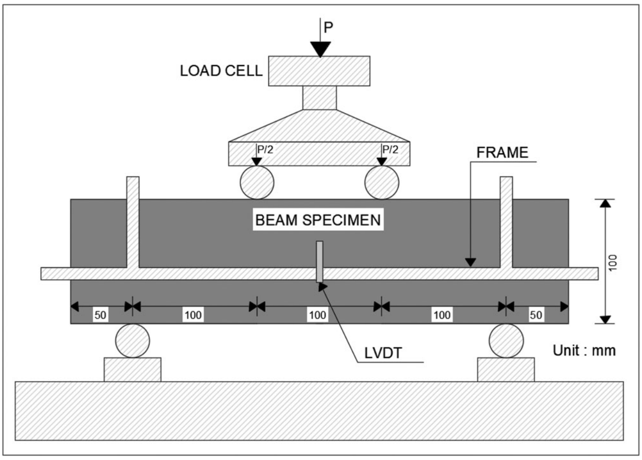


Figure 2. The test setup of prismatic beam specimens.

standards. As per the ASTM C1609 standard, δ_1 and δ_2 corresponded to first-peak load (P_1) and peak load (P_2), respectively (Figure 3). The first-peak point was identified in ASTM C1018 (ASTM, 1997) as the limit of proportionality (LOP). Also, the modulus of rupture (MOR) was a point where the softening section of the load vs. mid-span deflection diagram initiated after the mid-span deflection point at LOP. Besides, according to ASTM C1609, the toughness and flexural strength values at LOP, MOR, 0.5 mm and 2 mm were obtained from Eq. (1):

$$f = \frac{PL}{bh^2} \tag{1}$$

where, *f* stand for the flexural strength (MPa), *P* symbolized the load (N), *L*, *b* and *h* were the length (mm), width (mm) and height (mm) of prismatic beam specimens, respectively. The flexural toughness values termed as T (N-m) were determined from the areas under the load vs. mid-span deflection diagram at specified deflection points.

The flexural toughness factor (FTF) defined by JSCE standard (JSCE, 2005) was obtained by using Eq. (2).

$$FTF = (T_{L/150}/(L/150))(L/bh^2) \tag{2}$$

where, $T_{L/150}$ was the flexural toughness (N-mm) up to 2 mm. L was the length of span of prismatic beam specimens, $\delta_{L/150}$ was the mid-span deflection of 2 mm, b and h stand for the width and height of prismatic beam specimens. According to specified mid-span deflection points, the flexural properties of toughness, load carrying capacity and ductility index of the HFR-SCC mixtures were analysed.

4. Statistical method

The MLR analyses were used to predict the workability, mechanical and flexural properties of binary and ternary HFR-SCC while the effect of experimental parameters was evaluated by using ANOVA analysis. In the linear regression analysis, a linear forecaster function was used to model the data and thus, the output parameter was predicted. MLR models were used to interpret the correlation between a dependent and two or more independent variables through fitting a linear equation to data. The experimental variables were macro steel fibre volume (%), micro steel fibre volume fraction (%) and polypropylene fibre volume fraction (%). The common form of the multiple regression models defined by Deshpande et al. (2014) was given at Eq. (3). The slump-flow diameter, J-Ring, compressive, splitting tensile, flexural tensile strength and toughness experimental test results were evaluated by using the ANOVA.

$$Y = a_0 + a_1X_1 + a_2X_2 ... a_nX_n \tag{3}$$

where, a_0, a_1, $a_2 \ldots a_n$ were regression coefficients, X_1, $X_2 \ldots .X_n$ were independent variables and Y was the output.

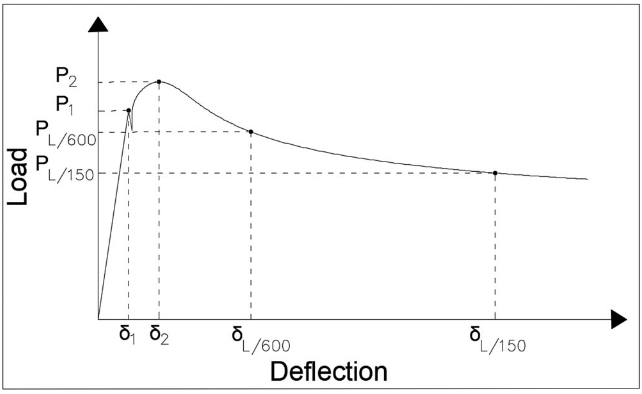


Figure 3. Flexural toughness parameters in ASTM C1609 standard.

5. Results and discussion

5.1. Workability test results and its statistical evaluation

The main workability conditions for SCC mixtures were good deformability, excellent stability and lower risk of blockage (Khayat, 1999). In order to obtain the workability conditions of the SCC as per EFNARC (2002), FA as mineral addition was replaced by pozzolanic cement in weight and HRWRA was added into the concrete mixtures. The slump-flow diameter, T_{500} and J-ring (H_2-H_1) test results were presented in Table 4.

The alteration of slump-flow diameter and T_{500} values for seven SCC mixtures having different micro fibre type and fibre combination were showed in Figure 4. It was observed that the slump-flow diameter and T_{500} values changed the range of 757.5 ± 17.5 mm and 4.2–6.8 sec, respectively. For the single macro steel FR-SCC mixtures, the slump-flow diameter values decreased with 1.9% for MAC1.00 and 3.54% for MAC1.25 compared to the control mixture without fibre. Also, the slump-flow diameter values of HFR-SCC with binary hybridiziation of macro and micro steel fibres decreased in proportion of 3.16% for MAC0.80_MIC0.20 and 4.43% for MAC1.00_MIC0.25. It could be said from here that when the total fibre and micro steel fibre content increased, the slump-flow diameter decreased while the T_{500} values increased. This can be attributed to the fact that micro steel fibre caused increase in the volume and surface area as result of lower density of micro steel fibre. All slump-flow diameter and J-ring test results were in the ranges suggested by EFNARC (2002) while T_{500} values did not satisfy the limit values of EFNARC (2002) due to the density and shape of steel fibre replaced by aggregate. Because, the amount of solid materials that will transport through the paste increased when it was included the steel fibres to SCC mixtures. In the literature, it was obtained by Turk et al. (2019), Liu et al. (2019) and Turk et al. (2021) that the flowability of FR-SCC mixtures reduced with the addition of micro steel fibres into the SCC mixtures.

The slump-flow values of the binary and ternary hybrid fibre reinforced mixtures containing PP (MAC1.00_PP0.25 and MAC0.80_MIC0.20_PP0.25) decreased with 5.06% and 6.33%, respectively, compared to CONTROL mixtures. In addition, T_{500} values were obtained as 6.5 and 6.8 sec for binary and ternary hybrid fibre reinforced mixtures with PP, respectively. It was clear that the inclusion of PP fibre into hybrid fibre reinforced SCC mixtures had a more negative impact than micro steel fibre on fresh concrete properties. In the study performed by Liu et al. (2019), it was observed that slump-flow diameter values of SCC mixtures decreased with PP fibre reinforcement. Another study showed that the inclusion of PP fibres into SCC mixtures greatly reduced the slump-flow diameter, that is, 0.3% PP fibre addition induced decrease in the slump-flow diameter values (from 720 mm to 430 mm) (Mazaheripour et al., 2011).

As can be seen from Table 4, the J-ring test results for CONTROL mixture was 1.7 mm, while those of the FR-SCC mixtures was in the range of 3.3–8 mm. Also, a total fibre and micro fibre volume fraction had an important effect on the heights of J-ring test. It can be seen from test results that J-ring value increased for single and HFR-SCC mixtures when the amount of fibre by volume increased from 1.0% to 1.25%. On the other hand, enhance in the volume of micro fibre induced increase in the heights of J-ring test values while the inclusion of PP fibre into both FR and HFR-SCC mixtures caused further increase in

Table 4. Workability properties of SCC.

Mixture Code	T_{500} (sec)	Slump-flow diameter (mm)	J-ring (H_2-H_1) (mm)
CONTROL	4.2	790	1.7
MAC1.00	5.3	775	3.3
MAC1.25	6	762	3.8
MAC0.80_MIC0.20	5.8	765	3.4
MAC1.00_MIC0.25	6.2	755	4.5
MAC1.00_PP0.25	6.5	750	7
MAC0.80_MIC0.20_PP0.25	6.8	740	8
Limits*	2–5	650–800	0–10

*Workability limits suggested by EFNARC.

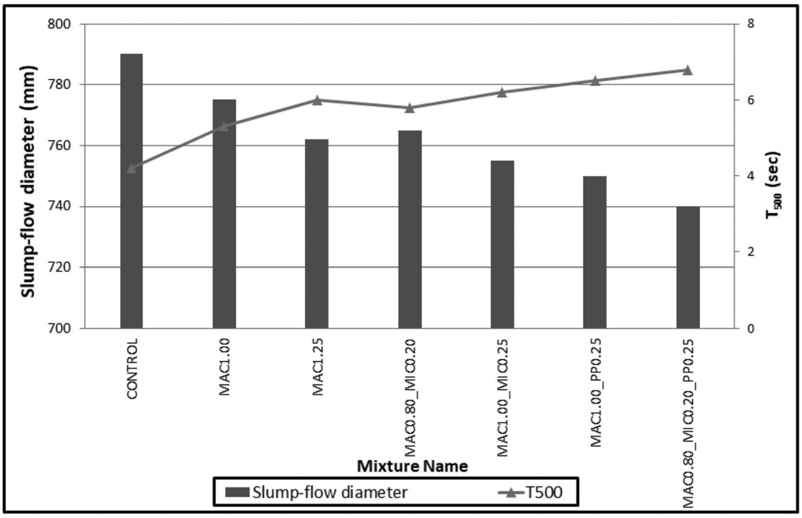


Figure 4. Slump-flow diameter and T_{500} values for SCC mixtures.

the J-ring heights with 112% for MAC1.00_PP0.25 and 135% for MAC0.80_MIC0.20_PP0.25. However, the use of micro steel fibre with macro steel fibre as hybrid binary blend caused further decrease in heights of J-ring with 3.03% for MAC0.80_MIC0.20 and 18.42% for MAC1.00_MIC0.25. In conclusion, the higher PP fibres inclusion significantly deteriorated the passing ability of HFR-SCC. This may be clearly attributed to the geometric properties of micro steel and PP fibre induced bundling because of its higher aspect ratio. In the literature, Turk et al. (2021) and Turk et al. (2019) also have obtained identical findings.

The ANOVA analysis was used to find the effect of experimental data variables on the workability test results. The data obtained as a result of ANOVA and MLR analysis performed by using slump-flow diameter test results were presented in Tables 5 and 6. As per the ANOVA analysis results given in Table 6, the most affecting variable for slump-flow diameter was obtained as PP fibre with 50.85% followed by micro steel fibre with 35.03% and macro steel fibre with 11.68%.

The MLR and ANOVA analyses were also made with the J-ring test results conducted for each SCC mixture, and the outputs were showed in Tables 7 and 8. According to results obtained from ANOVA analysis, the most effective parameter for J-ring test was found as PP fibre with 71.73% same as in the slump-flow test while the macro steel fibre had the lowest contribution ratio with 7.34%. This can be attributed to in the fact that PP fibres had lower density with higher aspect ratio and specific surface. Therefore, the number of fibres corresponding to the volume of concrete increased. Similar findings were found by Li et al. (2001) and Jabbour et al. (2021) who revealed from their works that PP fibres significantly increased water film thickness and packing density and thus, reducing workability of concrete. Moreover, in the study of Mohammed et al. (2019), it was found that the most effective experimental parameter for slump-flow diameter value was waste polyethylene terephthalate that was included into SCC mixtures as synthetic fibre.

In addition to ANOVA, Eq. (4) and (5) obtained from MLR was used to estimate the slump-flow diameter and J-ring height difference value (ΔH). These equations for slump-flow diameter and J-ring

Table 5. The statistical analysis for slump-flow diameter test results.

	df	SS	MS	F	Significance F
Regression	3	1597.781	532.594	40.011	0.006
Residual	3	39.933	13.311		
Total	6	1637.714			

Table 6. The MLR and ANOVA results for slump-flow diameter test results.

	Coefficients	Standard Error	t stat	P-value	Lower 95%	Higher 95%	Contribution (%)
Intercept	791.209	3.563	222.089	0.000	779.872	802.547	–
MACSF	−2019.747	377.499	−5.350	0.013	−3221.118	−818.376	11.68
MICSF	−6054.835	1279.483	−4.732	0.018	−10126.722	−1982.948	35.03
PP	−8790.698	1229.084	−7.152	0.006	−12702.191	−4879.204	50.85

Table 7. The statistical analysis for J-ring test results.

	df	SS	MS	F	Significance F
Regression	3	29.160	9.720	92.781	0.002
Residual	3	0.314	0.105		
Total	6	29.474			

Table 8. The MLR and ANOVA results for J-ring test results.

	Coefficients	Standard Error	t stat	P-value	Lower 95%	Higher 95%	Contribution (%)
Intercept	1.628	0.316	5.151	0.014	0.622	2.634	–
MACSF	162.513	33.490	4.853	0.017	55.934	269.093	7.34
MICSF	439.706	113.509	3.874	0.030	78.468	800.944	19.86
PP	1587.907	109.038	14.563	0.001	1240.899	1934.915	71.73

consisted of the variables that were the percent of fibres (macro, micro steel and polypropylene fibres) by volume.

$$SFD = 791.209 - 2019.747 * MACSF - 6054.835 * MICSF - 8790.698 * PP \quad (4)$$

$$J = 1.628 + 162.513 * MACSF + 439.706 * MICSF + 1587.907 * PP \quad (5)$$

where, SFD was the slump-flow diameter (mm), J was the J-ring test value (ΔH) (mm), MACSF was the percent of macro steel fibre by volume, MICSF was the percent of micro steel fibre volume and PP was the percent of polypropylene fibre volume.

As can be seen from Table 9, the statistical analysis was performed to determine the statistical parameters for the slump-flow diameter and J-ring. It was found from this analysis that R^2 values were 0.976 and 0.989 for the slump-flow diameter and J-ring, respectively. It can be seen clearly from here that there was a good correlation between experimental test results and predicted values.

Also, the efficiency ratio was calculated dividing by experimental and predicted results for slump-flow diameter and J-ring to reveal the accuracy of predicted results (see Table 10). It can be seen from this table that the efficiency ratio was approximately 1.

As seen displayed in Figures 5 and 6, the counter plots were drawn based on macro steel fibre volume fraction corresponding to micro steel or PP fibre to predict the slump-flow diameter and J-ring values for only binary HFR-SCC. As can be seen from the graphs, when a total volume of macro and micro fibres enhanced, the slump-flow diameter value decreased while the J-ring value increased.

5.2. Mechanical properties

5.2.1. Compressive strength results and its statistical evaluation

The average compressive strengths of 28 days and 90 days were displayed Table 11 and Figure 7. The SCC specimens in case of fibre hybridization had higher compressive strength than those of CONTROL and single macro steel FR-SCC specimens except for MAC1.00_PP0.25. Binary hybridization of macro and micro steel fibres induced increase in the compressive strength of MAC0.80_MIC0.20 and

Table 9. Summary outputs of statistical analysis of slump-flow diameter and J-ring test results.

Statistical parameters	Coefficient of slump-flow diameter	Coefficient of J-ring value
Multiple R	0.988	0.995
R square	0.976	0.989
Adjusted R square	0.951	0.979
Standard error	3.648	0.324
Observation	7	7

Table 10. Experimental and predicted values of slump-flow diameter and J-ring values.

	Slump-flow diameter (mm)			J-ring (mm)		
Mixture Code	Test	Predicted	$SFD_T/\ SFD_{Pr}$	Test	Predicted	$J_T/\ J_{Pr}$
CONTROL	790	791.21	0.998	1.7	1.63	1.043
MAC1.00	775	771.01	1.005	3.3	3.25	1.015
MAC1.25	762	765.96	0.995	3.8	3.66	1.038
MAC0.80_MIC0.20	765	762.94	1.003	3.4	3.81	0.892
MAC1.00_MIC0.25	755	755.87	0.999	4.5	4.35	1.034
MAC1.00_PP0.25	750	749.04	1.001	7	7.22	0.969
MAC0.80_MIC0.20_PP0.25	740	740.96	0.999	8	7.78	1.028

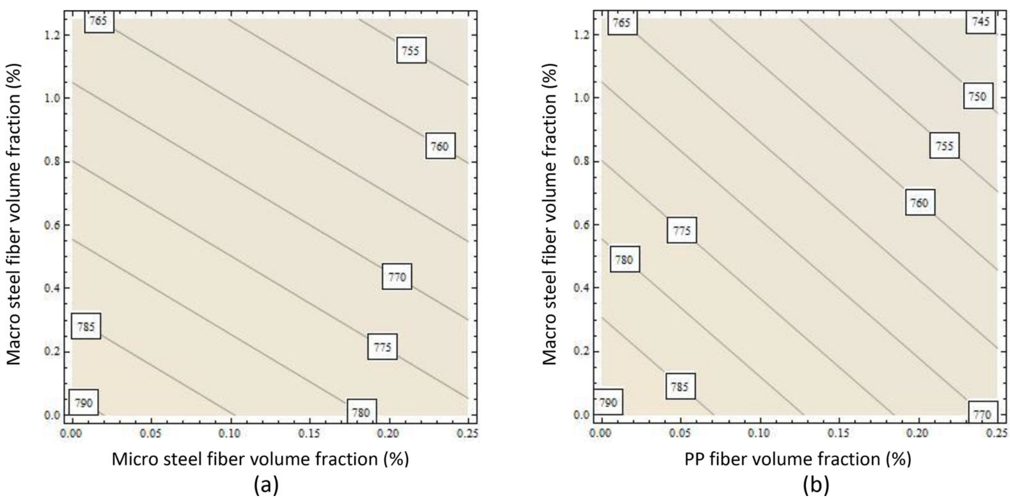


Figure 5. Effect of parameters on the slump-flow diameter (a) macro steel-micro steel fibre, (b) macro steel-PP fibre.

MAC1.00_MIC0.25 with 6.28% and 4%, respectively, compared to CONTROL specimens, however, the compressive strength was affected adversely with the inclusion of PP fibre into SCC for 90-day. This diminishment in the compressive strength of SCC specimens with PP fibre may be attributed to two reasons that one of them was the low tensile strength of PP fibres with 350 MPa and other was the concrete tendency toward the internal bleeding as result of the higher amount HRWRA utilization. This result was consistent with other researchers (Chen & Liu, 2005; Dawood & Hamad, 2015; Jabbour et al., 2021) who also found that the compressive strength of concrete reduced with the use of PP fibre. Moreover, the compressive strength of SCC specimens with ternary hybrid fibre increased with 19.15% and 5.17% for 28 and 90 days, respectively, compared to CONTROL specimens. It can be emphasized from here that, the inclusion of ternary hybrid fibre into SCC had more dominant effect in terms of increase in compressive strength compared to single and binary HFR-SCC for 28 curing day. Besides, in case of ternary hybrid fibre reinforcement, the amount of micro fibre (steel and PP) by volume increased and thus, the micro fibres became more efficient in delaying the micro crack improvement and preventing the crack propagation at certain levels (Haddadou et al., 2014; Neves & Fernandes de Almeida, 2005; Sahmaran et al., 2005; Sahmaran & Yaman, 2007). This may be attributed to the fact that micro steel and PP fibres had a significant effect in bridging the micro cracks due to their short lengths. In the literature, some researchers carried out experimental works on the addition of hybrid fibres and they emphasized that the inclusion of

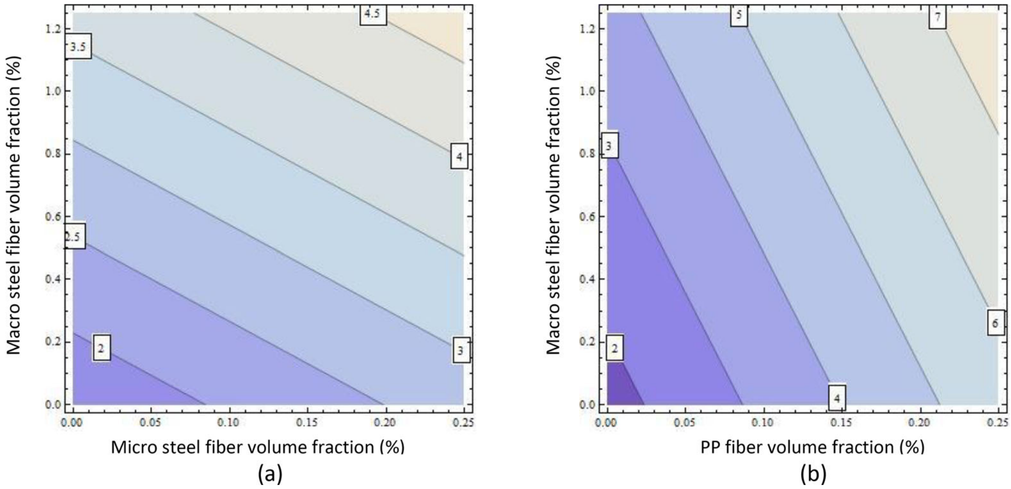


Figure 6. Effect of parameters on the J-ring test (a) macro steel-micro steel fibre, (b) macro steel-PP fibre.

macro and micro fibre into SCC had a positive contribution on the compressive strength (Afroz et al., 2019; Bassurucu & Turk, 2019; Turk et al., 2019, 2021).

The data obtained from MLR and ANOVA analysis carried out by using 90-day compressive strength test results that consisted of the average of three specimens for each FR-SCC mixture were displayed in Tables 12 and 13. According to the ANOVA analysis results given in Table 13, the most affecting parameter for compressive strength was micro steel fibre with 50.36% followed by PP fibre with 16.98% and macro steel fibre with 2.1%. This can be attributed to the fact that the micro steel fibres had a significant role in bridging of the micro cracks due to its aspect ratio and the tensile strength compared to PP fibre. However, both micro steel and PP fibres had a positive effect on compressive strength compared to macro fibres.

Besides, Eq. (6) determined by the MLR was used to predict the compressive strength at 90-day and the variables for this equation were the percent of macro, micro steel and PP fibres by volume.

$$C.S_{90\ days} = 72.213 - 79.370 * MACSF + 1917.121 * MICSF - 646.512 * PP \quad (6)$$

where, $C.S_{90\ days}$ was the compressive strength (MPa) at 90 day, MACSF was the percent of macro steel fibre, MICSF was the percent of micro steel fibre and PP was the percent of polypropylene fibre by volume.

Moreover, as given in Table 14, the statistical parameters were obtained from the statistical analysis to verify reliability in the estimation of compressive strength. It was found from this analysis that R^2 values were 0.694 for the compressive strength (Table 14). It can be seen explicitly from statistical analysis that there was a moderate correlation between experimental test results and predicted values determined. Because, it was difficult to estimate the compressive strength values in good correlation statistically due to the fact that increase in the fibre volume of SCC mixtures induced workability problems such as bundling compared to HFR-SCC with a total fibre volume of 1% (Turk et al., 2021).

In addition to these, the efficiency ratio was obtained dividing by experimental and predicted compressive strength results to reveal the accuracy of predicted results (see Table 15). It can be seen from this table that the efficiency ratio was approximately 1.

As showed in Figure 8, the counter plots were drawn based on macro steel fibre volume fraction corresponding to micro fibre (steel and PP) to estimate the effect of micro fibre type on the compressive strength values of binary HFR-SCC at 90 days. As can be seen from Figure 8(a), the use of micro steel fibre with macro steel fibre significantly increased the compressive strength with the average of 6.29% compared to only macro steel fibre reinforced SCC. Besides, the inclusion of PP fibre into only macro steel fibre reinforced SCC slightly reduced the compressive strength with the average of 2% (Figure 8(b)).

Table 11. The experimental test results for the mechanical properties of SCC mixtures.

	28-days			90-days		
Mixture Code	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Flexural Tensile Strength (MPa)	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Flexural Tensile Strength (MPa)
CONTROL	49.60	4.10	6.27	71.60	4.95	7.62
MAC1.00	48.40	5.60	10.88	73.80	7.10	11.14
MAC1.25	46.13	6.05	11.03	70.52	7.65	12.45
MAC0.80_MIC0.20	53.85	6.20	10.02	76.10	6.70	10.87
MAC1.00_MIC0.25	45.25	6.65	10.95	74.46	7.20	12.10
MAC1.00_PP0.25	48.20	6.35	11.58	68.30	7.25	13.29
MAC0.80_MIC0.20_PP0.25	59.10	7.49	12.45	75.30	8.15	14.37

5.2.2. Splitting tensile strength results and its statistical evaluation

The splitting tensile strengths of 28 days and 90 days were displayed Table 11 and Figure 9. The addition of macro steel, micro steel and PP fibres as binary and ternary blends into SCC significantly improved the splitting tensile strength as a result of the effect of different fibre hybridization. The ternary HFR-SCC specimens had highest rise in the splitting tensile strength for 28 and 90 curing days compared to CONTROL specimens. As can be seen from here, the use of macro steel fibres in HFR-SCC had very important effect in increasing the splitting tensile strength of SCC. Because macro steel fibre was a main ingredient for HFR composites due to a higher elastic modulus and lengths compared to micro fibres, the tensile stress were transferred more effectively with macro steel fibres and macro cracks were prevented (Haddadou et al., 2014). Similar results were also obtained by other researchers (Sahmaran et al., 2005; Turk et al., 2019, 2021) who obtained that the addition of macro steel fibres into SCC mixture had positive influence on the splitting tensile strength. Also, it can be emphasized that the binary hybrid blends including micro steel fibre induced increase in the splitting tensile strength of MAC0.80_MIC0.20 with 35.35% and MAC1.00_MIC0.25 with 45.45% compared to CONTROL specimens at 90 days. Moreover, the binary hybrid blends including PP also induced increase in the splitting tensile strength of with 46.46% because of adding in optimum volume into HFR-SCC mixture. In conclusion, PP fibre had more positive effect than micro steel fibre on the splitting tensile strength of HFR-SCC. This may be attributed to the fact that micro straight steel fibres would bridge micro cracks more effectively in case of the high-strength matrix.

The MLR and ANOVA analysis performed by using 90-day splitting tensile strength test results that consisted of the average of three specimens for each FR-SCC mixture was presented in Tables 16 and 17. According to ANOVA analysis results given in Table 17, the most affecting parameter for splitting tensile strength was PP fibre with 40.40% followed by macro steel fibre with 25.60% and micro steel fibre with 24.46%. This condition can be explained by the fact that the density of PP fibre was lower than that of micro steel fibre and thus, the filaments of PP fibre included was the more number by volume. Therefore, more micro cracks were bridged by PP fibre. In addition to these, straight micro steel fibre, which bridges the micro cracks, had lowest contribution to predict the splitting tensile strength of HFR-SCC due to insufficient strength of matrix in terms of its mechanical bond strength.

Also, Eq. (7) obtained from the MLR was used to estimate the splitting tensile strength at 90-day and the variables for this equation were the percent of macro, micro steel and PP fibres by volume.

$$S.T.S_{90\ days} = 4.943 + 198.319 * MACSF + 189.547 * MICSF + 313.023 * PP. \quad (7)$$

where, $S.T.S_{90\ days}$ was the splitting tensile strength (MPa) at 90 day, MACSF was the percent of macro steel fibre, MICSF was the percent of micro steel fibre and PP was the percent of PP fibre by volume.

As can be seen from Table 18, the statistical analysis was carried out to obtain the statistical parameters for the splitting tensile strength and R^2 value was 0.905. Moreover, it can be seen explicitly from statistical analysis that there was a good correlation between experimental test results and predicted values determined.

Besides, the efficiency ratio was calculated dividing by experimental and predicted splitting tensile strength results to reveal the accuracy of predicted results (see Table 19). It can be seen from this table that the efficiency ratio was approximately 1.

As showed in Figure 10, the counter plots were drawn based on macro steel fibre volume fraction corresponding to micro fibre (steel and PP) to predict the effect of micro fibre type on 90-day splitting

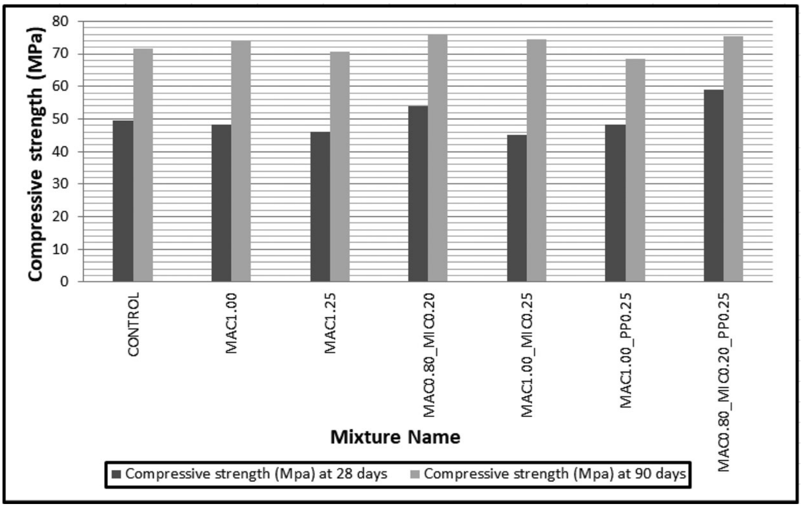


Figure 7. Average compressive strength results of SCC mixtures.

Table 12. The statistical analysis for compressive strength test results.

	df	SS	MS	F	Significance F
Regression	3	33.152	11.051	2.271	0.259
Residual	3	14.599	4.866		
Total	6	47.751			

Table 13. The MLR and ANOVA results for compressive strength test results.

	Coefficients	Standard Error	t stat	P-value	Lower 95%	Higher 95%	Contribution (%)
Intercept	72.213	2.154	33.525	0.000	65.358	79.069	–
MACSF	−79.370	228.247	−0.348	0.751	−805.755	647.015	2.1
MICSF	1917.121	773.614	2.478	0.089	−544.863	4379.105	50.36
PP	−646.512	743.141	−0.870	0.448	−3011.517	1718.494	16.98

Table 14. Summary outputs of statistical analysis of compressive strength test results.

Statistical parameters	Coefficient of compressive strength
Multiple R	0.833
R square	0.694
Adjusted R square	0.389
Standard error	2.206
Observation	7

Table 15. Experimental and predicted values of compressive strength values at 90-day.

	Compressive strength (MPa)		
Mixture Code	Test	Predicted	$C.S_T / C.S_{Pr}$
CONTROL	71.6	72.21	0.992
MAC1.00	73.8	71.42	1.033
MAC1.25	70.52	71.22	0.990
MAC0.80_MIC0.20	76.1	75.41	1.009
MAC1.00_MIC0.25	74.46	76.21	0.977
MAC1.00_PP0.25	68.3	69.80	0.979
MAC0.80_MIC0.20_PP0.25	75.3	73.80	1.020

tensile strength values of binary HFR-SCC. As can be seen diagram the counter plots, the inclusion of both micro steel and PP fibre into SCC mixtures induced increase in splitting tensile strength while PP fibre reinforcement had more positively influence on the splitting tensile strength than micro steel fibre.

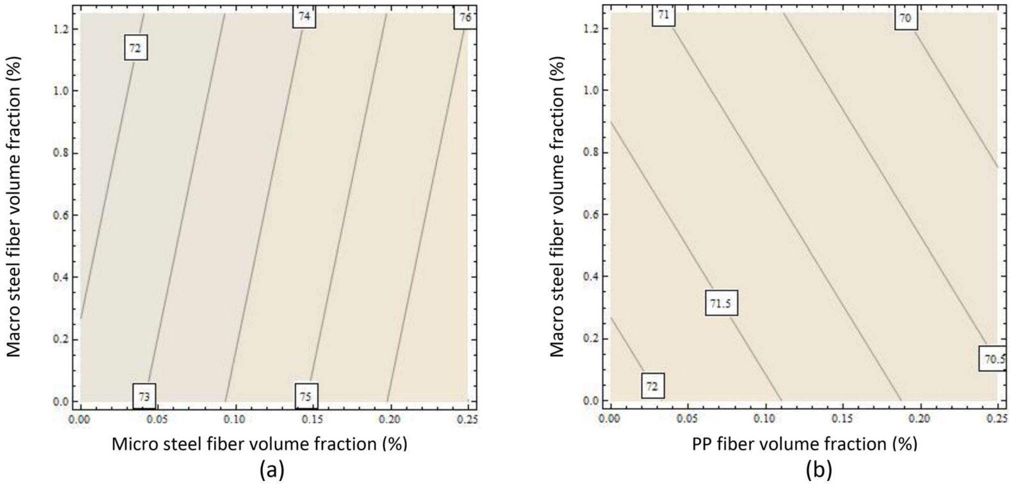


Figure 8. Effect of parameters on the compressive strength (a) macro steel-micro steel fibre, (b) macro steel-PP fibre.

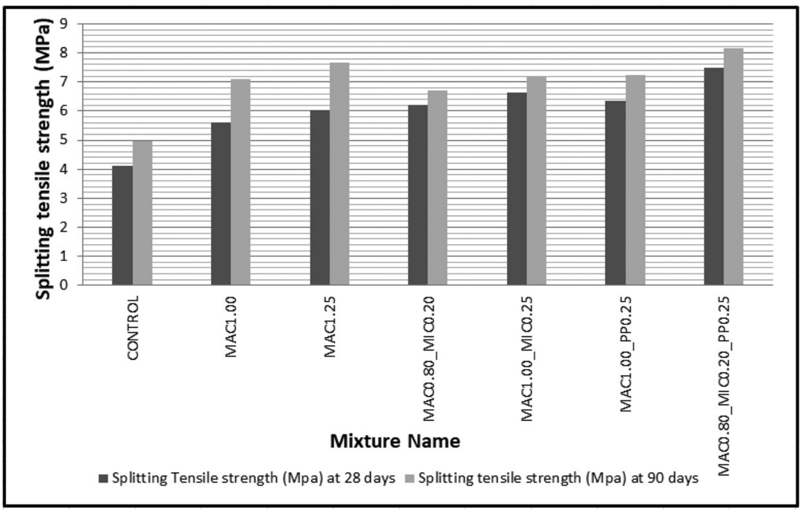


Figure 9. Average splitting tensile strength results of SCC mixtures.

5.3. Flexural performance

5.3.1. Flexural tensile strength results and its statistical evaluation

The results of flexural tensile strength tests were presented in Table 11 and Figure 11. The 28- and 90-day flexural tensile strengths of the CONTROL mixture were 6.27 MPa and 7.62 MPa, respectively. As seen from Table 11 and Figure 11, a combination of macro steel fibre with micro fibre (steel and/or PP fibres) had a positive effect on the flexural tensile strength of SCC specimens for all curing ages. In this study, all fibre combinations consisted of macro steel fibre because macro steel fibre is the essential constituent for hybrid fibre reinforced mixtures. It was also found similar result by Aboutair et al. (2020) who said that the existence of the steel fibres was main parameter to obtain high performance in flexion. The binary hybrid steel fibre reinforcement induced enhance in the flexural tensile strength of MAC0.80_MIC0.20 with 42.65% and MAC1.00_MIC0.25 with 58.79% compared to CONTROL specimens for 90 curing ages. Besides, the use of 0.25% PP fibre with 1.0% macro steel caused increase in the flexural tensile strength of with 74.4%. Also, the highest rise in flexural strength of SCC specimens was obtained for the ternary hybrid fibre mixture as 98.56% and 88.58% for 28 and 90 days, respectively, compared to CONTROL specimens. As can be seen from here, the ternary fibre hybridization had a positive effect on the flexural

Table 16. The statistical analysis for splitting tensile strength test results.

	df	SS	MS	F	Significance F
Regression	3	5.563	1.854	9.481	0.049
Residual	3	0.587	0.196		
Total	6	6.150			

Table 17. The MLR and ANOVA results for splitting tensile strength test results.

	Coefficients	Standard Error	t stat	P-value	Lower 95%	Higher 95%	Contribution (%)
Intercept	4.943	0.432	11.446	0.001	3.569	6.317	–
MACSF	198.319	45.759	4.334	0.023	52.694	343.944	25.60
MICSF	189.547	155.094	1.222	0.309	−304.030	683.124	24.46
PP	313.023	148.984	2.101	0.126	−161.112	787.158	40.40

Table 18. Summary outputs of statistical analysis of splitting tensile strength test results.

Statistical parameters	Coefficient of splitting tensile strength
Multiple R	0.951
R square	0.905
Adjusted R square	0.809
Standard error	0.442
Observation	7

tensile strength of HFR-SCC. Because it had higher synergy because of including two different micro fibre (steel and PP) and thus, there was an advantage in terms of the formation and propagation of micro cracks up to a certain extent because they bridged more micro crack. Similar results were found by some researchers (Afroz et al., 2019; Liu et al., 2019) who obtained that the hybridization of steel and PP fibres increased the efficiently flexural tensile strength as result of a positive synergy.

The MLR and ANOVA analysis carried out by using 90-day flexural tensile strength test results that consisted of the average of three specimens for each FR-SCC mixture was displayed in Tables 20 and 21. As per ANOVA analysis results presented in Table 21, the PP fibre was the most effective experimental variable with 55.96% as in the splitting tensile strength for flexural tensile strength while macro steel fibre had lowest contribution with 19.21%. This may be attributed to the fact that the filaments of PP fibre was added more number by volume because the density of PP fibre was lower than that of micro steel fibre resulting in more micro cracks were bridged by PP fibre.

Also, Eq. (8) determined by the MLR was used to predict the flexural tensile strength at 90 curing day and the experimental variables for this equation were the percent of macro, micro steel and PP fibres by volume.

$$F.T.S_{90\ days} = 7.541 + 360.865 * MACSF + 413.146 * MICSF + 1051.163 * PP \tag{8}$$

where, $F.T.S_{90\ days}$ was the flexural tensile strength (MPa) at 90 day, MACSF was the percent of macro steel fibre, MICSF was the percent of micro steel fibre and PP was the percent of PP fibre by volume.

According to the Table 22, the statistical analysis was performed to determine the statistical outputs for the flexural tensile strength and R^2 value was 0.972. Besides, it can be seen obviously from statistical analysis that there was a good correlation between experimental test results and estimated values obtained.

Moreover, the efficiency ratio was obtained dividing by experimental and predicted flexural tensile strength results to reveal the accuracy of predicted results (see Table 23). It can be seen from this table that the efficiency ratio was approximately 1.

As seen displayed in Figure 12, the counter plots were drawn based on macro steel fibre volume fraction corresponding to micro fibre (steel and PP) to estimate the flexural tensile strength values at 90 days according to the micro fibre type for binary HFR-SCC. As can be seen the counter plot diagrams, it was obtained that the use of micro fibre (steel and PP) together with macro steel fibre increased the flexural tensile strength while PP fibre had a better effect than micro steel fibre.

Table 19. Experimental and predicted values of splitting tensile strength values at 90-day.

	Splitting tensile strength (MPa)		
Mixture Code	Test	Predicted	STS_T/ STS_{Pr}
CONTROL	4.95	4.94	1.002
MAC1.00	7.1	6.93	1.025
MAC1.25	7.65	7.42	1.030
MAC0.80_MIC0.20	6.7	6.91	0.969
MAC1.00_MIC0.25	7.2	7.4	0.973
MAC1.00_PP0.25	7.25	7.71	0.940
MAC0.80_MIC0.20_PP0.25	8.15	7.69	1.060

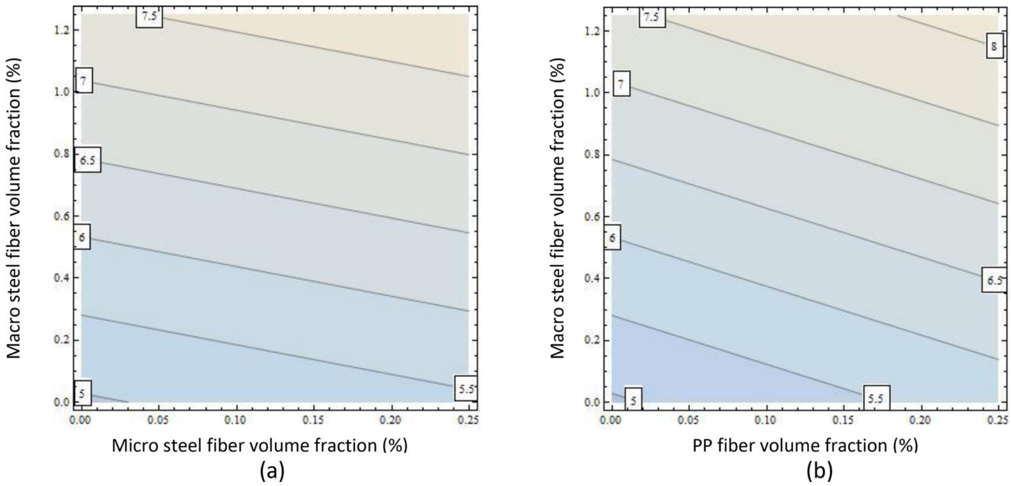


Figure 10. Effect of parameters on the splitting tensile strength (a) macro steel-micro steel fibre, (b) macro steel-PP fibre.

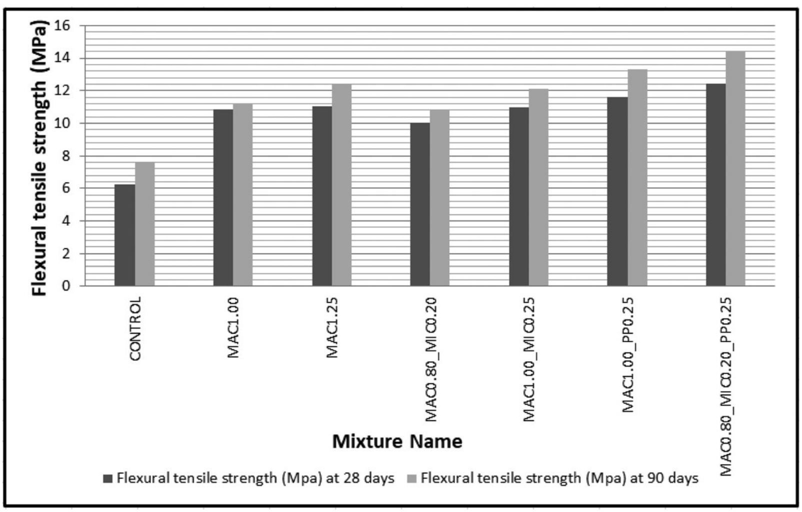


Figure 11. Average flexural tensile strength results of SCC mixtures.

5.3.2. Load-midspan deflection diagrams and cracking properties

To evaluate the effect of micro fibres on the flexural behaviour of HFR-SCC specimens, the load-midspan deflection diagrams were used. Figure 13 showed the load-midspan deflection diagrams of single and hybrid fibre reinforced SCC having different combination of macro steel fibre with micro fibre (steel and/ or PP fibres) for 28 and 90 curing day. The diagrams were plotted by using the average values of three

Table 20. The statistical analysis for flexural tensile strength test results.

	df	SS	MS	F	Significance F
Regression	3	27.233	9.078	34.253	0.008
Residual	3	0.795	0.265		
Total	6	28.028			

Table 21. The MLR and ANOVA results for flexural tensile strength test results.

	Coefficients	Standard Error	t stat	P-value	Lower 95%	Higher 95%	Contribution (%)
Intercept	7.541	0.503	15.002	0.001	5.941	9.141	–
MACSF	360.865	53.266	6.775	0.007	191.350	530.380	19.21
MICSF	413.146	180.537	2.288	0.106	−161.404	987.695	21.99
PP	1051.163	173.426	6.061	0.009	499.245	1603.081	55.96

prismatic beam specimens determined from four-point bending tests for each FR-SCC mixture. The load vs. mid-span deflection diagram in all fibre reinforced concrete mixtures generally consisted of three main stages: linear elastic, deflection-hardening and -softening parts (Kim et al., 2011). There was no any crack in the elastic region and the multiple cracking was observed in the cement matrix at deflection-hardening region while the deflection-softening region including localized cracks determined the ductility of fibre reinforced concrete (Tufekci & Gokce, 2017). It was apparent from the load vs. mid-span deflection diagrams that in all HFR-SCC specimens the linear elastic part of the curves was identical and all FR-SCC specimens exhibited deflection-hardening behaviour for all curing days. On the other hand, in case of addition of ternary hybrid fibre, deflection-hardening behaviour was more apparent than that of other FR-SCC specimens. Because it had higher synergy due to hybridization of two different micro fibre (steel and PP) with macro steel fibre and thus, it can be bridged more micro crack and delayed the formation and propagation of micro cracks up to a certain extent.

As for flexural behaviour of FR-SCC mixtures, ternary hybrid fibre reinforcement also had a positive influence on the load-carrying capacity. Because the highest load-carrying capacity were obtained in the ternary HFR-SCC mixtures with 0.80% macro steel, 0.20% micro steel and 0.25% PP fibre followed by binary HFR-SCC mixtures having 1.00% macro steel and 0.25% PP fibre, MAC1.25 and MAC1.00_MIC0.25 for all curing days. It can be concluded from here that the addition of PP fibre with macro steel fibre as both ternary and binary fibre blends had more a positive effect than micro steel fibre on the ultimate load capacity. Similar results also were found by the other researchers (Afroz et al., 2019; Liu et al., 2019; Rashiddadash et al., 2014; Turk et al., 2021), that the micro (steel and PP) fibres in hybrid blends affected the positively ultimate load capacity as result of a positive synergy.

The crack patterns were important to categorize the flexural behaviour of HFR-SCC specimens. The formation and propagation of cracks for single FR-SCC was different from HFR-SCC. Because, in the single FR-SCC specimens, no further cracks after first crack formed in the matrix before the failure. As for the HFR-SCC specimens, further cracks occurred in the matrix as the mid-span deflection increased after the first crack formation. Multiple crack behaviour of the SCC specimens was dependent on the total volume fraction and the combination of fibre. It can be seen from Figure 14 that when the addition of micro steel and PP fibres with macro steel into SCC mixtures induced prominently the multiple crack behaviour of the HFR-SCC specimens for all curing days. This result was consistent with the study of Niu et al. (2020). They found that the use of high-performance PP fibre instead of the increased stirrup ratio more effectively prevented crack development. Also, it can be addressed from here that ternary HFR-SCC specimens displayed more micro cracks having smaller width compared to binary and single fibre reinforced SCC under four-point bending. The measured average crack width of ternary HFR-SCC specimens changed between 76 μm and 600 μm for all curing days. Therefore, it may be said that ternary HFR-SCC had an important advantage in terms of service life of reinforced concrete structure. Similar results were found by Sahmaran et al. (2007) and Şahmaran and Li (2009).

5.3.3. Flexural toughness results and its statistical evaluation

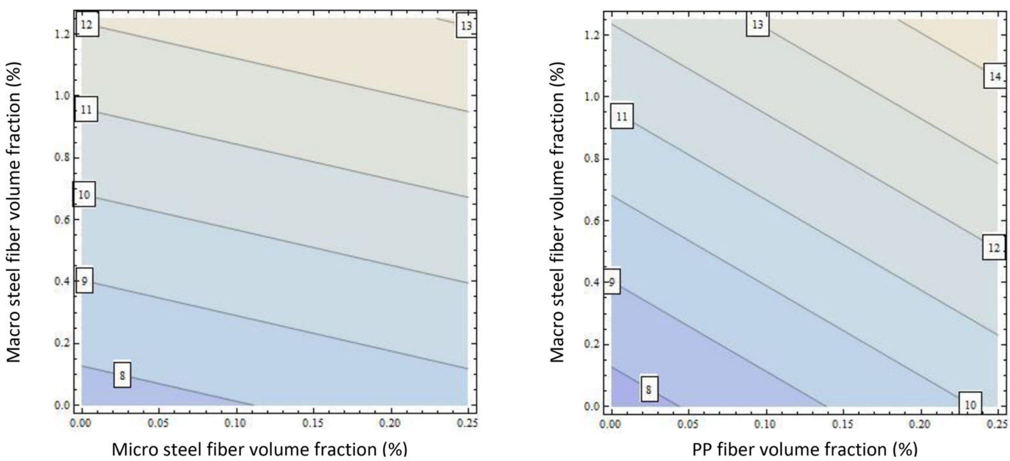
The flexural toughness of composites was quite vital in terms of resistance against seismic loads for the especially high-rise buildings as well as blast loads. The mid-span deflection (d), flexural strength (f) and toughness (T) values of all FR-SCC specimens for LOP, MOR, L/600 and L/150 were presented for 28 and

Table 22. Summary outputs of statistical analysis of flexural tensile strength test results.

Statistical parameters	Coefficient of compressive strength
Multiple R	0.986
R square	0.972
Adjusted R square	0.943
Standard error	0.515
Observation	7

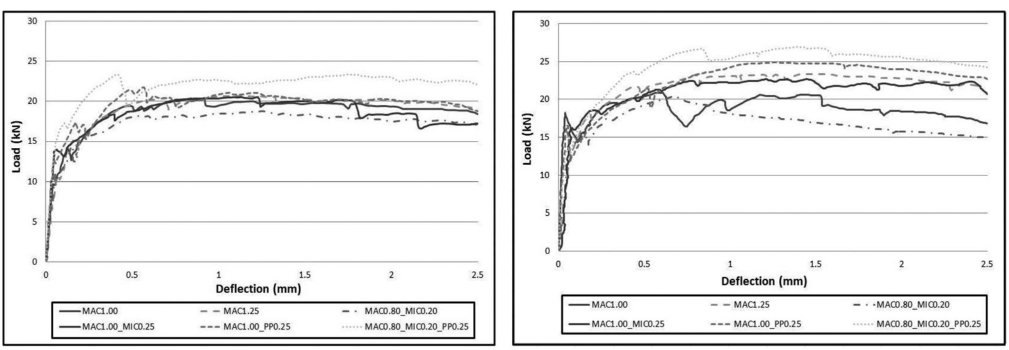
Table 23. Experimental and predicted values of flexural tensile strength values at 90-day.

	Flexural tensile strength (MPa)		
Mixture Code	Test	Predicted	FTS_T/ FTS_{Pr}
CONTROL	7.62	7.54	1.010
MAC1.00	11.14	11.15	0.999
MAC1.25	12.45	12.05	1.033
MAC0.80_MIC0.20	10.87	11.25	0.966
MAC1.00_MIC0.25	12.1	12.18	0.993
MAC1.00_PP0.25	13.29	13.78	0.964
MAC0.80_MIC0.20_PP0.25	14.37	13.88	1.035



(a) (b)

Figure 12. Effect of parameters on the flexural tensile strength (a) macro steel-micro steel fibre, (b) macro steel-PP fibre.



(a) (b)

Figure 13. Flexural test load-midspan deflection diagrams (a) 28 days (b) 90 days.

(a)

(b)

Figure 14. Images of MAC0.80_MIC0.20_PP0.25 specimens after flexural test (a) 28 days (b) 90 days.

90 curing days in Tables 24 and 25, respectively, as well as Figure 15. As can be seen from Tables 24 and 25, the flexural toughness values in the LOP were approximately the identical in all FR-SCC for all curing days except for 28-day T_{LOP} of ternary HFR-SCC.

As shown in Figure 15, ternary HFR-SCC specimens (MAK0.80_MIK0.20_PP0.25) had highest flexural toughness values at deflection points MOR, L/600 and L/150 followed by MAC1.00_PP0.25, MAC1.00_MIC0.25 and MAC1.25 for all curing days. Also, in moderately high-strength concrete, ternary hybridization of the fibres was the best option to obtain the highest flexural toughness while in the binary hybridizations, the use of PP fibre with macro steel fibre was more effective than micro steel fibre. It can be concluded from here that PP fibre had very important role in the improvement of flexural toughness of HFR-SCC. Because, the slip of o PP fibres were inhibited by means of the adhesion and friction bond between PP fibres and matrix due to the interfacial zone denseness as result of the formation of CSH by the pozzolanic reaction of FA (Bezerra et al., 2006) and thus, PP fibres could merely elongate and tighten. Then, a second crack might occur when the tensile strength of the PP fibre was surpassed in any section of the concrete. Moreover, another work investigated the effect of the addition of high-performance PP fibres instead of increased stirrup ratio into column specimens. It was found that the energy absorption capacity and ductility of columns increased (Niu et al., 2020). In conclusion, the flexural toughness of the concrete was significantly improved because of the formation of many additional fibre bridges (Felekoğlu et al., 2009). Also, Turk et al. (2021), Rashiddadash et al. (2014) and Dawood and Hamad (2015) found that hybrid fibre reinforced concrete mixtures had better toughness performance than single fibre reinforced concrete mixtures.

Moreover, as per JSCE (JSCE, 2005), the flexural toughness factors of single, binary and ternary fibre reinforced SCC specimens consisting of macro steel, micro steel and PP fibres for 28 and 90 curing days were displayed in Figure 16. The ternary HFR-SCC mixtures had the highest flexural toughness factors with 11.71 and 13.08 for 28 and 90 curing days, respectively, followed by binary HFR-SCC specimens including 1% macro steel fibre with 0.25% PP while binary HFR-SCC specimens having 0.8% macro steel fibre with 0.2% micro steel fibre had the lowest flexural toughness factor. In conclusion, flexural toughness values of binary and ternary HFR-SCC specimens calculated according to ASTM C1609 and JSCE codes were consistent with the load-midspan deflection curves.

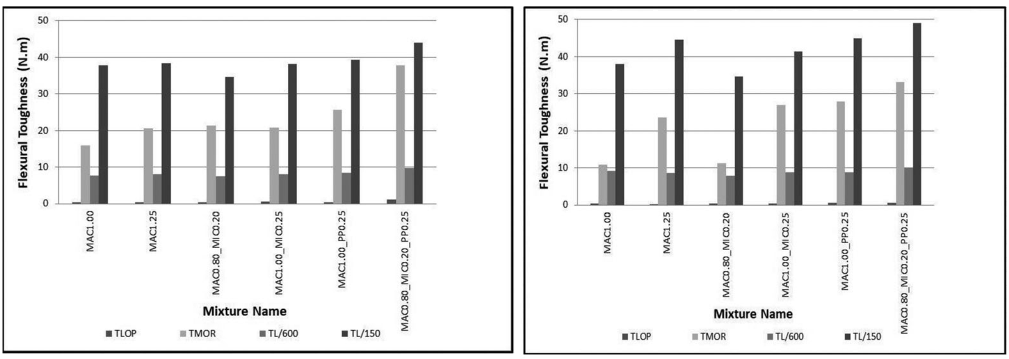
In addition to these, as seen in Table 26, ductility index values of single, binary and ternary hybrid FR-SCC mixtures were calculated as the proportion of the midspan deflection value at MOR to the first crack deflection value (LOP) (Naaman Ae, 1995). This index means that if ($\delta_{MOR}/\delta_{LOP}$) ratio was higher fibre reinforced concrete was more ductile. The midspan deflection values of LOP for all curing ages were very similar to each other and altered between 0.04 and 0.09 mm for all FR-SCC specimens. Because the midspan deflection values at the first crack (LOP) was more influenced by matrix strength than fibre bridging (Yoo et al., 2017). As can be seen from Table 26, the ductility index value of ternary HFR-SCC specimens was the highest with 19.44 and 28 for the 28 and 90 days, respectively. Also, the ductility index of the binary hybrid fibre reinforced including 1.00% macro steel and 0.25% PP fibre was higher than that of SCC specimens having 1.00% macro steel and 0.25% micro steel fibre for 28- and 90-day. Hence, it can be clearly said that the inclusion of PP fibre into binary and ternary HFR-SCC mixtures caused a better ductility performance than micro steel fibre.

Table 24. Flexural toughness test results of FR-SCC at 28-day.

Mixture Code	d_{LOP}	d_{MOR}	$d_{L/600}$	$d_{L/150}$	f_{LOP}	f_{MOR}	$f_{L/600}$	$f_{L/150}$	T_{LOP}	T_{MOR}	$T_{L/600}$	$T_{L/150}$
MAC1.00	0.04	0.92	0.5	2	5.15	10.88	10.29	10.32	0.29	15.88	7.69	37.73
MAC1.25	0.07	1.14	0.5	2	5.76	11.03	10.48	10.75	0.45	20.64	8.07	38.27
MAC0.80_MIC0.20	0.06	1.26	0.5	2	5.99	10.02	9.69	9.30	0.40	21.42	7.55	34.70
MAC1.00_MIC0.25	0.05	1.13	0.5	2	7.31	10.95	10.00	9.87	0.53	20.72	8.11	38.23
MAC1.00_PP0.25	0.05	1.33	0.5	2	6.77	11.58	11.32	10.77	0.31	25.63	8.46	39.28
MAC0.80_MIC0.20_PP0.25	0.09	1.75	0.5	2	9.01	12.45	10.62	12.19	1.20	37.71	9.67	43.92

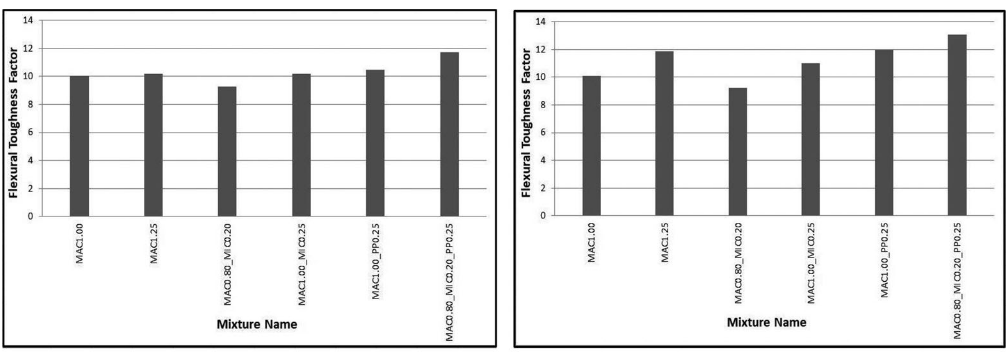
Table 25. Flexural toughness test results of FR-SCC at 90-day.

Mixture Code	d_{LOP}	d_{MOR}	$d_{L/600}$	$d_{L/150}$	f_{LOP}	f_{MOR}	$f_{L/600}$	$f_{L/150}$	T_{LOP}	T_{MOR}	$T_{L/600}$	$T_{L/150}$
MAC1.00	0.04	0.59	0.5	2	9.50	11.14	10.89	9.82	0.37	10.86	9.21	37.94
MAC1.25	0.06	1.16	0.5	2	5.27	12.45	11.12	12.13	0.22	23.67	8.60	44.60
MAC0.80_MIC0.20	0.05	0.67	0.5	2	6.35	10.87	10.31	8.42	0.31	11.23	7.94	34.64
MAC1.00_MIC0.25	0.06	1.33	0.5	2	8.30	12.10	11.03	11.62	0.38	27.00	8.76	41.35
MAC1.00_PP0.25	0.05	1.28	0.5	2	8.84	13.29	11.35	12.81	0.57	27.94	8.88	44.83
MAC0.80_MIC0.20_PP0.25	0.05	1.40	0.5	2	6.94	14.37	12.80	13.57	0.48	33.21	9.87	49.05



(a) (b)

Figure 15. Flexural toughness of FR-SCC at (a) 28 days, (b) 90 days.



(a) (b)

Figure 16. Flexural toughness factors as per JSCE at (a) 28 days, (b) 90 days.

The MLR and ANOVA analysis results for 90-day flexural toughness values of all FR-SCC specimens at L/150 (2 mm) was showed in Tables 27 and 28. According to ANOVA analysis results displayed in Table 28, the most effective parameter was obtained as PP fibre with 39.83% followed by macro steel fibre with 25.42% and micro steel fibre with 21.29%. This may be attributed to the interfacial zone denseness due to the pozzolanic reaction of FA with CH because the adhesion and friction bond between PP fibres

Table 26. Ductility index of single, binary and ternary hybrid FR-SCC.

Mixture Code	Ductility index at 28 days	Ductility index at 90 days
MAC1.00	23	14.75
MAC1.25	16.29	19.33
MAC0.80_MIC0.20	21	13.4
MAC1.00_MIC0.25	22.6	22.17
MAC1.00_PP0.25	26.6	25.6
MAC0.80_MIC0.20_PP0.25	19.44	28

Table 27. The statistical analysis for flexural toughness test results.

	df	SS	MS	F	Significance F
Regression	3	117.275	39.092	4.285	0.195
Residual	2	18.244	9.122		
Total	5	135.519			

Table 28. The MLR and ANOVA results for flexural toughness test results.

	Coefficients	Standard Error	t stat	P-value	Lower 95%	Higher 95%	Contribution (%)
Intercept	9.550	13.675	0.698	0.557	−49.289	68.389	–
MACSF	2718.105	1213.408	2.240	0.154	−2502.767	7638.978	25.42
MICSF	2277.053	1580.066	1.441	0.286	−4521.422	9075.527	21.29
PP	4260	1208.121	3.526	0.072	−938.123	9458.123	39.83

Table 29. Summary outputs of statistical analysis of flexural toughness test results.

Statistical parameters	Coefficient of flexural toughness
Multiple R	0.930
R square	0.865
Adjusted R square	0.663
Standard error	3.020
Observation	6

Table 30. Experimental and predicted values of flexural toughness values at 90-day.

	Flexural toughness (N-m)		
Mixture Code	Test	Predicted	T_T/ T_{Pr}
MAC1.00	37.94	36.73	1.033
MAC1.25	44.6	43.53	1.025
MAC0.80_MIC0.20	34.64	35.85	0.966
MAC1.00_MIC0.25	41.35	42.42	0.975
MAC1.00_PP0.25	44.83	47.38	0.946
MAC0.80_MIC0.20_PP0.25	49.05	46.50	1.055

and matrix improved. Thus, PP fibres could merely elongate and tighten resulting in a second crack (Felekoğlu et al., 2009).

Also, Eq. (9) obtained from the MLR was used to estimate the flexural toughness at 90 curing day and the experimental variables for this equation were the percent of macro, micro steel and PP fibres by volume.

$$T_{L/150} = 9.550 + 2718.105 * MACSF + 2277.053 * MICSF + 4260 * PP \quad (9)$$

where, $T_{L/150}$ was the flexural toughness (N-m) at 90 day, MACSF was the percent of macro steel fibre, MICSF was the percent of micro steel fibre and PP was the percent of polypropylene fibre by volume.

According to the Table 29, the statistical analysis was carried out to obtain the statistical parameters for the flexural toughness and R^2 value was 0.865. Also, it can be seen clearly from statistical analysis that there was a good correlation between experimental test results and predicted values determined from MLR.

In addition to ANOVA analysis outputs, the efficiency ratio was also calculated dividing by experimental and predicted flexural toughness results to reveal the accuracy of predicted results (See Table 30). It can be seen from this table that the efficiency ratio was approximately 1.

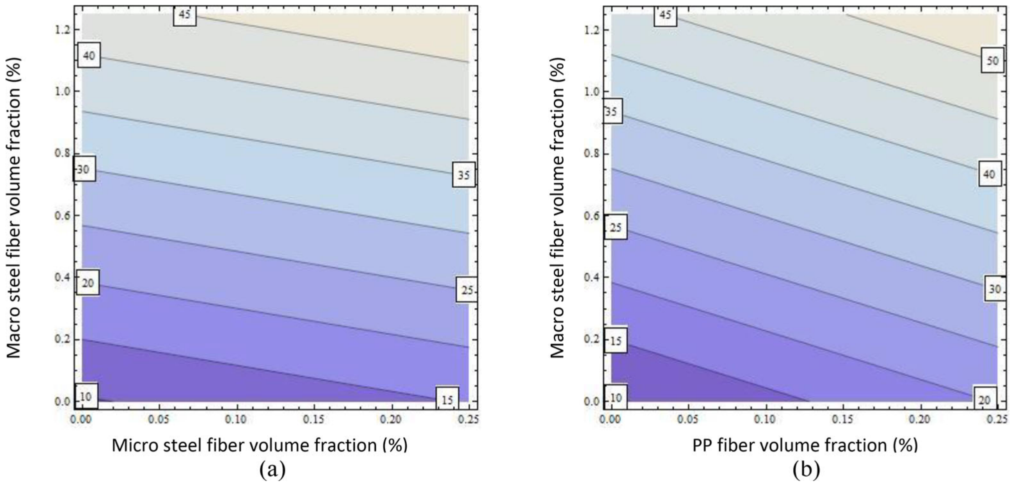


Figure 17. Effect of parameters on the flexural toughness (a) macro steel-micro steel fibre, (b) macro steel-PP fibre.

As showed in Figure 17, the counter plots were drawn based on macro steel fibre volume fraction versus micro fibre (steel and PP) to estimate the effect of micro fibre type on 90-day flexural toughness values of binary HFR-SCC. As can be seen the counter plots, the addition of both micro steel and PP fibre into SCC mixtures caused increase in flexural toughness while PP fibre reinforcement had more positively effect on the flexural toughness performance compared to micro steel fibre.

6. Conclusions

In this study, the effects of micro fibre type (steel and PP) and different fibre combinations (binary and ternary blend) on the fresh, hardened properties and flexural performance of HFR-SCC were investigated. With this work, it was highlighted in design of HFR-SCC in terms of micro fibre type and fibre combination based on fresh and hardened properties as well as flexural performance as experimental and statistical. The following conclusions can be drawn:

- The addition of PP fibre into SCC mixtures had a more negative impact than micro steel fibre on workability properties. Also, ANOVA analysis gave similar result that the most effective parameter for slump-flow diameter and J-ring tests was PP fibre. Besides, the MLR predicted the slump-flow diameter and J-ring values with high accuracy of 97.6% and 98.9%, respectively.
- The use of micro steel fibre as binary and ternary blends had positive influence on 90-day compressive strength of FR-SCC while the opposite was true for PP fibre. This was consistent with ANOVA analysis that the most affecting parameter for compressive strength was micro steel fibre with 50.36%.
- The highest splitting tensile and flexural strength for all curing ages was obtained from micro steel and PP with macro steel fibre reinforced SCC as ternary blend though PP fibre had more positively influence than micro steel fibre. Moreover, splitting tensile and flexural strength values were estimated with 90.5% and 97.2% accuracy, respectively, by using MLR while the most affecting parameter for these properties was PP fibre based on ANOVA analysis.
- HFR-SCC specimens as ternary blend had more prominent deflection-hardening behaviour compared to other FR-SCC specimens as result of a numbers of micro cracks with smaller width resulting in the longer service life, especially in the applications of industrial building and infrastructure. Besides, for the same volume fraction, the use of PP fibre with macro steel fibre as binary blend had more a positive effect than micro steel fibre on the ultimate load capacity.
- The highest flexural toughness and ductility index was obtained from SCC specimens having ternary hybridization of the fibres. As for micro fibre type, the use of PP with macro steel fibre as binary blend had a better effect on the flexural toughness performance and ductility index compared to

micro steel fibre. Besides, the most effective parameter for flexural toughness was PP fibre with 39.83% while flexural toughness values were estimated with 86.5% accuracy by using MLR.

- In addition to all these, it can be addressed that macro steel fibre for HFR composites was an essential constituent especially in terms of splitting and flexural tensile strength of composites. Moreover, it has been thought that the use of PP as micro fibre in HFR composites will ensure important contributions in terms of toughness and ductility especially in beam to column connections.

Disclosure statement

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. We would like to declare that the study described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. The authors listed have approved the manuscript that is enclosed.

Funding

The financial support for this work was provided by Scientific Research Projects Committee of Inonu University, Turkey (Project No: FDK-2019-1974). Their support was gratefully acknowledged.

References

Aboutair, A., Chaid, R., & Molez, L. (2020). Physico-mechanical and microstructural characterization of concretes ultra-high performance matrix fibre. *European Journal of Environmental and Civil Engineering*, *24*(12), 2032–2045. https://doi.org/10.1080/19648189.2018.1498808

Afroz, M., Venkatesan, S., & Patnaikuni, I. (2019). Effects of hybrid fibres on the development of high volume fly ash cement composite. *Construction and Building Materials*, *215*, 984–997. https://doi.org/10.1016/j.conbuildmat.2019.04.083

ASTM. (1997). ASTM C1018-97 Standard test method for flexural toughness and first-crack strength of fibre-reinforced concrete (using beam with third-point loading). ASTM Standard. https://doi.org/10.1520/C1018-97

ASTM. (2002). ASTM C78-Standard test method for flexural strength of concrete (using simple beam with). ASTM International.

ASTM. (2005). ASTM C 1609/C 1609M-05-Standard test method for flexural performance of fibre-reinforced concrete (using beam with third-point loading). ASTM International. https://doi.org/10.1520/C1609

ASTM. (2008). ASTM C39-Standard test method for compressive strength of cylindrical concrete specimens. ASTM.

ASTM. (2011). ASTM C 496/C 496M-Standard test method for splitting tensile strength of cylindrical concrete specimens. ASTM International. https://doi.org/10.1520/C0496

Balcikanli Bankir, M., & Sevim, U. K. (2020). Performance optimization of hybrid fibre concrete according to mechanical properties. *Construction and Building Materials*, *261*, 119952. https://doi.org/10.1016/j.conbuildmat.2020.119952

Bassurucu, M., & Turk, K. (2019). Effect of curing regimes on the engineering properties of hybrid fibre reinforced concrete. *The International Journal of Energy & Engineering Sciences*, *4*(2), 26–42.

Bezerra, E. M., Joaquim, A. P., Savastano, H., John, V. M., & Agopyan, V. (2006). The effect of different mineral additions and synthetic fibre contents on properties of cement based composites. *Cement and Concrete Composites*, *28*(6), 555–563. https://doi.org/10.1016/j.cemconcomp.2006.02.001

Chen, B., & Liu, J. (2005). Contribution of hybrid fibres on the properties of the high-strength lightweight concrete having good workability. *Cement and Concrete Research*, *35*(5), 913–917. https://doi.org/10.1016/j.cemconres.2004.07.035

Dawood, E. T., & Hamad, A. J. (2015). Toughness behaviour of high-performance lightweight foamed concrete reinforced with hybrid fibres. *Structural Concrete*, *16*(4), 496–507. https://doi.org/10.1002/suco.201400087

Deshpande, N., Londhe, S., & Kulkarni, S. (2014). Modeling compressive strength of recycled aggregate concrete by Artificial Neural Network, Model Tree and Non-linear Regression. *International Journal of Sustainable Built Environment*, *3*(2), 187–198. https://doi.org/10.1016/j.ijsbe.2014.12.002

Ding, Y., Zeng, W., Wang, Q., & Zhang, Y. (2020). Topographical analysis of fractured surface roughness of macro fibre reinforced concrete and its correlation with flexural toughness. *Construction and Building Materials*, *235*, 117466. https://doi.org/10.1016/j.conbuildmat.2019.117466

EFNARC. (2002). Specification and guidelines for self-compacting concrete. *Report from EFNARC*. https://doi.org/0953973344

EFNARC. (2005). The European guidelines for self-compacting concrete. The European Guidelines for Self Compacting Concrete.

Fallah-Valukolaee, S., & Nematzadeh, M. (2020). Experimental study for determining applicable models of compressive stress–strain behaviour of hybrid synthetic fibre-reinforced high-strength concrete. *European Journal of Environmental and Civil Engineering*, *24*(1), 34–59. https://doi.org/10.1080/19648189.2017.1364297

Felekoğlu, B., Tosun, K., & Baradan, B. (2009). Effects of fibre type and matrix structure on the mechanical performance of self-compacting micro-concrete composites. *Cement and Concrete Research*, *39*(11), 1023–1032. https://doi.org/10.1016/j.cemconres.2009.07.007

Haddadou, N., Chaid, R., Ghernouti, Y., & Adjou, N. (2014). The effect of hybrid steel fibre on the properties of fresh and hardened self-compacting concrete. *Journal of Building Materials and Structures*, *1*, 65–76.

Jabbour, R., Assaad, J. J., & Hamad, B. (2021). Cost-to-performance assessment of polyvinyl alcohol fibres in concrete structures. *Mechanics of Advanced Materials and Structures*, *0*(0), 1–20. https://doi.org/10.1080/15376494.2021.1882625

JSCE. (2005). Method of test for flexural strength and flexural toughness of fibre reinforced concrete. JSCE Standard.

Khayat, K. H. (1999). Workability, testing, and performance of self-consolidating concrete. *ACI Materials Journal*, *96*(3), 346–353. https://doi.org/10.14359/632

Khelifa, M. R., Leklou, N., Bellal, T., Hebert, R. L., & Ledesert, B. A. (2018). Is alfa a vegetal fibre suitable for making green reinforced structure concrete? *European Journal of Environmental and Civil Engineering*, *22*(6), 686–706. https://doi.org/10.1080/19648189.2016.1217792

Kim, D. j., Naaman, A. E., & El-Tawil, S. (2008). Comparative flexural behaviour of four fibre reinforced cementitious composites. *Cement and Concrete Composites*, *30*(10), 917–928. https://doi.org/10.1016/j.cemconcomp.2008.08.002

Kim, D. J., Park, S. H., Ryu, G. S., & Koh, K. T. (2011). Comparative flexural behaviour of Hybrid Ultra High performance fibre reinforced concrete with different macro fibres. *Construction and Building Materials*, *25*(11), 4144–4155. https://doi.org/10.1016/j.conbuildmat.2011.04.051

Kina, C., Turk, K., Atalay, E., Donmez, I., & Tanyildizi, H. (2021). Comparison of extreme learning machine and deep learning model in the estimation of the fresh properties of hybrid fiber-reinforced SCC. *Neural Computing and Applications*, *33, 11641-11659*. https://doi.org/10.1007/s00521-021-05836-8

Li, V. C., Wang, S., & Wu, C. (2001). Tensile strain-hardening behaviour or polyvinyl alcohol engineered cementitious composite (PVA-ECC). *ACI Materials Journal*, *98*(6), 483–492. https://doi.org/10.14359/10851

Liu, X., Wu, T., Yang, X., & Wei, H. (2019). Properties of self-compacting lightweight concrete reinforced with steel and polypropylene fibres. *Construction and Building Materials*, *226*, 388–398. https://doi.org/10.1016/j.conbuildmat.2019.07.306

Mahapatra, C. K., & Barai, S. V. (2018). Hybrid fibre reinforced self compacting concrete with fly ash and colloidal nano silica: A systematic study. *Construction and Building Materials*, *160*, 828–838. https://doi.org/10.1016/j.conbuildmat.2017.11.131

Manjunath, R., Narasimhan, M. C., & Kumar, S. (2020). Effects of fibre addition on performance of high-performance alkali activated slag concrete mixes: An experimental evaluation. *European Journal of Environmental and Civil Engineering*, 1–16. https://doi.org/10.1080/19648189.2020.1776771

Mazaheripour, H., Ghanbarpour, S., Mirmoradi, S. H., & Hosseinpour, I. (2011). The effect of polypropylene fibres on the properties of fresh and hardened lightweight self-compacting concrete. *Construction and Building Materials*, *25*(1), 351–358. https://doi.org/10.1016/j.conbuildmat.2010.06.018

Mohammed, M. K., Al-Hadithi, A. I., & Mohammed, M. H. (2019). Production and optimization of eco-efficient self compacting concrete SCC with limestone and PET. *Construction and Building Materials*, *197*, 734–746. https://doi.org/10.1016/j.conbuildmat.2018.11.189

Naaman Ae, R. H. W. (1995). Characterization of high performance fibre reinforced cement composites. *Proceedings of the Second International RILEM Workshop USA*, 1–24. https://doi.org/10.1520/C1609

Neves, R. D., & Fernandes de Almeida, J. C. O. (2005). Compressive behaviour of steel fibre reinforced concrete. *Structural Concrete*, *6*(1), 1–8. https://doi.org/10.1680/stco.6.1.1.62458

Niu, J., Bian, Y., & Zuo, F. (2020). Study on the seismic performance of high-performance polypropylene fibre-reinforced lightweight aggregate concrete columns. *European Journal of Environmental and Civil Engineering*, 1–19. https://doi.org/10.1080/19648189.2020.1830306

Ozawa, K., Maekawa, K., Kunishima, M., & Okamura, H. (1989). Development of high performance concrete based on the durability design of concrete structures. *Proceeding of the Second East - Asia and Pacific Conference on Structural Engineering and Construction (EASEC - 2)*, *1*, 445–450.

Rashiddadash, P., Ramezanianpour, A. A., & Mahdikhani, M. (2014). Experimental investigation on flexural toughness of hybrid fibre reinforced concrete (HFRC) containing metakaolin and pumice. *Construction and Building Materials*, *51*, 313–320. https://doi.org/10.1016/j.conbuildmat.2013.10.087

Şahmaran, M., & Li, V. C. (2009). Durability properties of micro-cracked ECC containing high volumes fly ash. *Cement and Concrete Research*, *39*(11), 1033–1043. https://doi.org/10.1016/j.cemconres.2009.07.009

Sahmaran, M., Li, M., & Li, V. C. (2007). Transport properties of engineered cementitious composites under chloride exposure. *ACI Materials Journal*, *104*(6), 604–611. https://doi.org/10.14359/18964

Sahmaran, M., & Yaman, I. O. (2007). Hybrid fibre reinforced self-compacting concrete with a high-volume coarse fly ash. *Construction and Building Materials*, *21*(1), 150–156. https://doi.org/10.1016/j.conbuildmat.2005.06.032

Sahmaran, M., Yurtseven, A., & Ozgur Yaman, I. (2005). Workability of hybrid fibre reinforced self-compacting concrete. *Building and Environment*, *40*(12), 1672–1677. https://doi.org/10.1016/j.buildenv.2004.12.014

Thomas, J., & Ananth, R. (2007). Mechanical Properties of Steel Fiber-Reinforced Concrete. *Journal of Materials in Civil Engineering*, *19*(5), 385–392. https://doi.org/10.33899/rengj.2006.45308 https://doi.org/10.1061/(ASCE)0899-1561(2007)19:5(385)

Tufekci, M. M., & Gokce, A. (2017). Development of heavyweight high performance fibre reinforced cementitious composites (HPFRCC) – Part I: Mechanical properties. *Construction and Building Materials*, *148*, 559–570. https://doi.org/10.1016/j.conbuildmat.2017.05.009

Turgut, P., Turk, K., & Bakirci, H. (2012). Segregation control of SCC with a modified L-box apparatus. *Magazine of Concrete Research*, *64*(8), 707–716. https://doi.org/10.1680/macr.11.00144

Turk, K. (2012). Viscosity and hardened properties of self-compacting mortars with binary and ternary cementitious blends of fly ash and silica fume. *Construction and Building Materials*, *37*, 326–334. https://doi.org/10.1016/j.conbuildmat.2012.07.081

Turk, K., & Bassurucu, M. (2021). Bond strength of full-scale beams with blended short and long steel fibre. *Pamukkale University Journal of Engineering Sciences*, *27*(3), 274–280. https://doi.org/10.5505/pajes.2020.34846

Turk, K., Bassurucu, M., & Bitkin, R. E. (2021). Workability, strength and flexural toughness properties of hybrid steel fibre reinforced SCC with high-volume fibre. *Construction and Building Materials*, *266*, 120944. https://doi.org/10.1016/j.conbuildmat.2020.120944

Turk, K., Karatas, M., & Ulucan, Z. C. (2010). Effect of the use of different types and dosages of mineral additions on the bond strength of lap-spliced bars in self-compacting concrete. *Materials and Structures*, *43*(4), 557–570. https://doi.org/10.1617/s11527-009-9511-1

Turk, K., Kina, C., & Oztekin, E. (2020). Effect of macro and micro fibre volume on the flexural performance of hybrid fibre reinforced SCC. *Advances in Concrete Construction*, *10*(3), 257–269. https://doi.org/10.12989/acc.2020.10.3.257

Turk, K., Oztekin, E., & Kina, C. (2019). Self-compacting concrete with blended short and long fibres: experimental investigation on the role of fibre blend proportion. *European Journal of Environmental and Civil Engineering*, 1–14. https://doi.org/10.1080/19648189.2019.1686069

Yoo, D. Y., Kim, S. W., & Park, J. J. (2017). Comparative flexural behavior of ultra-high-performance concrete reinforced with hybrid straight steel fibers. *Construction and Building Materials*, *132*, 219–229. https://doi.org/10.1016/j.conbuildmat.2016.11.104

Yu, R., Spiesz, P., & Brouwers, H. J. H. (2015). Development of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC): Towards an efficient utilization of binders and fibres. *Construction and Building Materials*, *79*, 273–282. https://doi.org/10.1016/j.conbuildmat.2015.01.050