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RESEARCH ARTICLE

THE EFFECT OF SYNTHETIC FIBER TYPE ON FRESH, HARDENED AND TOUGHNESS PROPERTIES OF HSFR-SCC

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ABSTRACT

This study presents the experimental results about the effects of Polyvinyl-alcohol (PVA) and Polypropylene (PP) fibers on the fresh and mechanical properties including compressive, splitting tensile strength, modulus of rupture (MOR) as well as toughness of the hybrid fiber reinforced self-compacting concrete (SCC). PVA and PP fibers were added into SCC mixtures having only macro steel fiber and also having binary hybridization of both macro and micro steel fiber. The results showed that the use of micro steel fiber replaced by macro steel fiber improved the workability, compressive and splitting tensile strength, MOR and toughness and also caused reduction in the weight loss percentage compared to the use of only macro steel fiber. Moreover, it was emphasized that PVA or PP enhanced the residual flexural performance of SCC, generally, while it negatively influenced the workability and the residual strengths according to the use of single steel fiber and binary steel fiber hybridization. Compared to the effect of synthetic fibers, PP had slightly more positive effect in the view of workability while PVA enhanced the residual mechanical properties more.

Keywords: Hybrid fiber reinforced self-compacting concrete, Polypropylene fiber, Polyvinyl-alcohol fiber, Strength, Toughness

1. INTRODUCTION

Self-compacting concrete (SCC) was first developed on 20th century in Japan which is one of the countries where earthquakes were experienced most frequently. It was started to be used due to the need for concrete that can be placed into reinforced concrete elements without applying any compression process [1]. It can be classified as high-performance concrete due to having low water-binder ratio achieved by the use of hyper plasticizer additives and being more resistant against external effects. In order to classify a mixture as SCC, the limit values of the workability tests determined by EFNARC [2] committee must be achieved.

The first studies on fiber reinforced concrete (FR-C) were carried out in the mid-20th century to examine the mechanical behavior of steel FR-C [3]. FR-C is defined as concrete reinforced with randomly oriented fibers in the matrix [4]. The use of fibers into the concrete prevents the crack formation. Fibers affect the tensile, compressive and flexural strengths as well as some properties such as creep, shrinkage, impact and fatigue according to many parameters such as type, volume fraction, shape, distribution of fiber, tensile performance, etc. The most important increase in performance of FR-C compared to concrete with no fiber is the energy absorption capacity of concrete during fracture. Fiber types used in the construction industry are generally steel, plastic, synthetic and ceramic-glass fibers. Steel fiber is one of the most widely used fibers in concrete due to their excellent mechanical properties [5]. However, the service life of concrete elements reinforced with steel fiber may be limited by changes in hardened properties due to corrosion in certain specific environments [6]. On the other hand, synthetic fibers offer important benefits as they are resistant to corrosion, chemically inert

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and stable in alkaline environment [7]. In the past, the aim of the use of synthetic fiber was to minimize the segregation in the fresh state and to resist the stresses obtained from the volumetric change [8]. In today, in order to increase the fracture energy to the cementitious matrices, monofilament and multifilament synthetic fibers were developed. The most commonly utilized synthetic fibers in cement-based composites are PVA, PP, polyethylene (PE). These fibers can improve the ductility of the concrete and reduce cracking. PVA fiber has highest modulus elasticity and durability among all synthetic fibers so it performs well in preventing the crack propagation. Besides, the adherence formed by the matrix with PVA is so high [9]. Dong et al [10] found from their experimental work that the utilization of 0.75% PVA fiber enhanced the porosity, mechanical properties of cementitious composites. In the study of Mostofinejad et al [11] PVA and PP fibers were utilized into ultra-high performance concrete and it was found that PVA fiber enhanced the flexural performance in terms of first-crack strength, ultimate flexural strength and toughness. However, it was emphasized that the use of PP and PP as hybrid showed strain-hardening behaviour and superior mechanical characteristics. Nam et al [12] also investigated the influence of PP and PVA fiber on the cementitious composites and found that PVA fiber showed better freezing thawing resitance. Guo et al [13] observed that the incorporation of PVA and PP fibers caused maximum compressive and flexural strengths with regards to unreinforced samples.

FR-C produced from the hybridization of more than one discontinuous fiber type into traditional concrete matrix is called hybrid fiber reinforced concrete (HFR-C) [14, 15]. In the case of using synthetic and steel fibers (SFs) as hybrid, SFs provide high ductility and superior tensile strength to the matrix and delay the crack initiation and propagation, while PP can alleviate the breakdown of concrete exposed to high temperature [16]. Liu et al [17] noted that the incorporation of steel and PP as hybrid created a positive synergy by effectively improving the strength as well as flexural performance of HFR-C. In the experimental work of Dawood and Hamad [18], it was concluded that flexural toughness increased with increasing fiber volume. Besides, they noted that the best flexural performance for cement-based composite materials was achieved when the fibers were used as hybrid. Ding et al [19] used an improved topographic analysis method and argued that the use of hybrid fiber into cementitious composites will be an important solution in the future to increase the flexural toughness of concrete which is so vital for durability.

There are some experimental and theoretical studies and standards to evaluate the flexural toughness parameters of FR-composites. The most widely used methods are ASTM C1609 [20] and JSCE [21]. The study of Banthia and Trottier [22] found that there are some limitations in all methods for determining the flexural toughness of FR-composites so it makes sense to compare these different methods.

In this study, PVA and PP synthetic fibers were added into single and HSFR-SCC mixtures and thus, binary and ternary HFR-SCC mixtures were designed. As mentioned in the literature, the utilization of fibers as hybrid provides beneficial properties for concrete in terms of mechanical and durability aspects. Within this scope, the incorporation of steel fibers with synthetic fibers is also a promising way to improve the performance of concrete due to their synergies. However, different types of synthetic fibers can cause different impacts on the fresh and hardened properties of steel fiber reinforced concrete mixtures/samples. The objective of this experimental work is to investigate the effect of the use of different synthetic fibers into single and HSFR-SCC mixtures on fresh, hardened and flexural properties. Besides, flexural parameters such as toughness, ductility were also calculated based on ASTM C1609 and JSCE.

2. EXPERIMENTAL METHODS

2.1. Materials

CEM I 42.5R Portland Cement (PC) and Class-F fly ash (FA) were used as binder in the production of fiber reinforced SCC mixtures. The chemical and physical properties of these materials were given in Table 1. The aggregate groups were arranged as 0-5 mm and 5-10 mm according to the maximum aggregate size. The finer aggregate group (0-5 mm) had specific gravity of 2.49 and water absorption of 2.2%. The specific gravity and water absorption of coarse aggregate group (5-10 mm) was 2.63 and 0.3%, respectively. A polycarboxylate-based Water Reducer (WR) with the specific gravity of 1.06 was used as chemical admixture to ensure the workability of fresh SCC. A macro SF and three different micro fiber types were utilized in the fiber reinforced SCC mixtures. As micro fiber, a micro SF and two different synthetic fibers names as PVA and PP were used. The properties of these fibers were listed in Table 2.

Table 1. The physical and chemical properties of PC and FA

Binders	Composition (%)									Specific Gravity	Surface Area (cm^2/g)
	CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	SO_3	K_2O	Na_2O	LOI		
PC	58.85	19.41	3.67	5.58	2.12	3.16	0.69	0.61	6.07	3.06	4891
FA	1.07	63.04	6.77	21.63	-	0.10	-	-	2.60	2.30	2900

Table 2. The properties of fibers

Fiber	Type	Picture	Shape	Length (mm)	Aspect Factor	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Density (g/cm^3)
MA	Macro Steel		Hooked-end	60	65	1345	200	7.8
MI	Micro Steel		Straight	6	40	3000	200	7.2
PVA	Micro Synthetic		Straight	8	200	1600	41	1.3
PP	Micro Synthetic		Straight	6	240	350	-	0.91

2.2. Experimental Program

In the determination of the mix proportions, the workability tests (slump-flow, t_{50} and J-ring) were taken into account according to EFNARC [23] which determines the self-compacting ability conditions of the mixtures. Within this scope, binder content for all SCC mixtures was used as 600 kg/m^3 for PC and 300 kg/m^3 for FA and the water/binder ratio was kept constant as 0.23. WR was added into all SCC mixtures to ensure the limit values (650-800 mm) determined by EFNARC [23] for the slump-flow test.

A total of seven SCC mixtures were designed by using four different types and shapes of fibers including a control mixture with no fiber in this study. Table 3 shows SCC mix designations. A single FR-SCC having only 1% macro SF (MA1) and SCC mixture reinforced with binary fiber hybridization of both micro and macro SFs (MA0.75_MI0.25) were designed. In order to investigate the effect of PVA and PP fiber on SFR-SCC, these FR-SCC mixtures were also combined with both PVA and PP separately. By this way, binary blends of macro steel and synthetic fibers (MA1_PVA & MA1_PP) and ternary blends of macro steel, micro steel and synthetic fibers (MA0.75_MI0.25_PVA & MA0.75_MI0.25_PP) were obtained. The steel and synthetic fiber content of the mixtures were kept constant as 1% and 0.25% by volume, respectively.

Table 3. The proportions of mixtures

Mix Code	Binders (kg/m^3)		Water (kg/m^3)	Aggregates (kg/m^3)		Steel Fiber (%)		Synthetic Fiber (%)		WR (kg/m^3)
	PC	FA		(0-5)	(5-10)	MA	MI	PVA	PP	
Control	600	300	203	973.8	171.8	0	0	0	0	15
MA1	600	300	204	952.0	168.0	1	0	0	0	16
MA1_PVA	600	300	204	918.5	162.1	1	0	0.25	0	20
MA1_PP	600	300	204	922.6	162.8	1	0	0	0.25	18
MA0.75_MI0.25	600	300	204	949.5	167.6	0.75	0.25	0	0	19
MA0.75_MI0.25_PVA	600	300	204	914.0	161.3	0.75	0.25	0.25	0	22
MA0.75_MI0.25_PP	600	300	204	914.0	161.3	0.75	0.25	0	0.25	22

2.3. The Preparation of the Fiber Reinforced SCC Samples

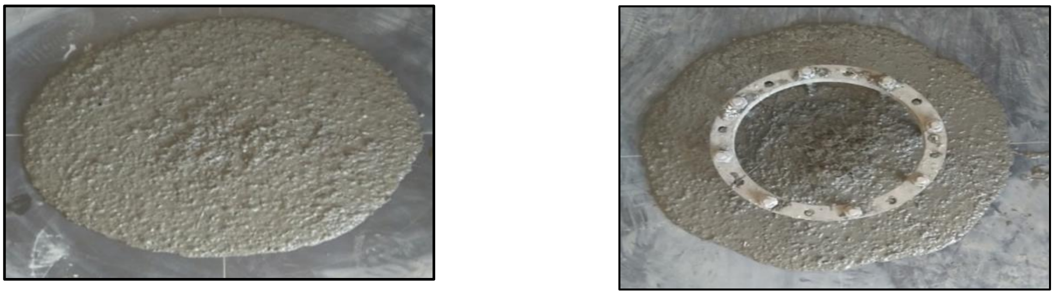
Aggregates were first put, followed by SFs and 2/3 of mixing water and they were mixed for 3 minutes into the mixer. Afterwards, binders and the remaining mixing water with WR were added and mixed for additional 5 minutes. In order to prevent the clumping of synthetic fibers, they were added into the mixture little by little after 7 minutes. The prepared SCC mixtures were placed into molds without any compression process. The samples were kept for 24 hours by covering them with a nylon cover to prevent evaporation. After they were removed from the molds, they were placed in a curing pool at 23±2°C and cured for a total of 90 days.

2.4. Procedures for Testing

2.4.1. Fresh SCC tests

At first, to determine the fresh unit weight values of the mixtures, the prepared mixtures were filled into a 100x200 mm cylinder molds without applying any compression process. The measured weight was divided by the volume of the mold to calculate the fresh unit weight of the designed mixtures.

The fresh concrete properties of SCC with no fiber and FR-SCC mixtures were evaluated based on the workability test methods determined by EFNARC [23]. Within this scope, slump-flow and J-Ring tests were carried out as shown in Fig. 1. The purpose of using slump-flow test method was to measure the filling ability of concrete. In this test, without wasting time, the Abrams cone placed on a flat plate was filled with the prepared mixture without applying the compression process and lifted upwards. When the spreading of concrete is complete, the slump-flow diameter was measured by taking the average of the two perpendicular dimensions (D_s). The time elapsed from the removal of the cone until the fresh SCC reached a diameter of 500 mm was measured and recorded as t_{50} time. In order to measure the ability fresh SCC to pass through obstacles, J-ring test was performed. Unlike the slump-flow test, a 300 mm diameter ring was used, for this test procedure. Then, the heights formed in the inner and outer part of the ring were measured and the difference was taken (ΔH). Similar to slump-flow test, the flow diameter (D_J) and t_{50j} were also measured in the J-ring test.

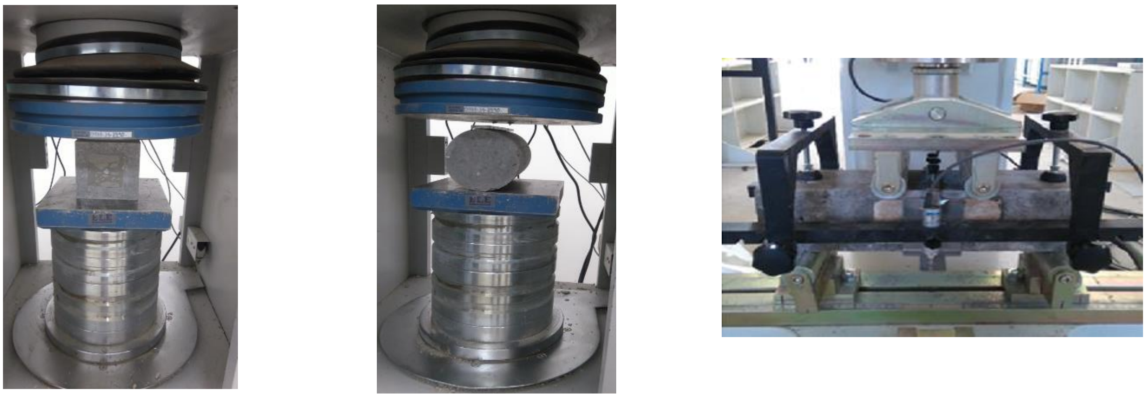


(a) (b)

Figure 1. Fresh SCC tests: (a) Slump-flow, (b) J-Ring

2.4.2. Hardened SCC tests

In order to attain the hardened properties of SCC with no fiber and FR-SCC specimens, the compressive, splitting tensile and flexural strength tests were performed on 90 days curing samples. Compressive strength (f_c) test was applied to 100x100x100 mm cubic samples based on ASTMC39 [24] and splitting tensile strength (f_{ct}) test was performed on ϕ100x200mm cylinder specimens according to ASTM C496 / C496M-17 [25]. To measure the flexural tensile strength (f_f), the four-point bending test was carried out on 400mm x 100mm x 100mm prism specimens with a loading speed of 0,003 mm/sec according to ASTM C1609 [20] with displacement control. A photo of the test equipments were provided in Fig. 2. Three specimens were produced and tested for all designed mixtures and tests and the average of the test results were calculated.



(a) (b) (c)

Figure 2. Hardened SCC tests: (a) f_c, (b) f_{ct}, (c) f_f

2.4.3. Evaluation methods of flexural toughness

Bending behavior of fiber reinforced cement based composite specimens is defined as deflection-hardening or deflection-softening. In the deflection-hardening behavior, a higher load-bearing capacity is observed after the initial crack formation, while in the deflection-softening behavior, the load-bearing capacity decreased. In ASTM C1609 [20], the first peak is used because, as proved by Kim [26], it is difficult to determine the initial peak strength of fiber reinforced concrete specimens exhibiting deflection-hardening behavior. The flexural strength of the samples were calculated using the equation given in Equation (1) according to ASTM C1609 [20].

$$f_f = \frac{F.L}{b.h^2} \tag{1}$$

where f_f is the flexural strength (MPa), F is the maximum load (N), L, b and h are the length, width and height of the specimen in mm, respectively.

The fracture modulus is defined as modulus of rupture (MOR) on the load-deflection curve observed after the limit of proportionality (LOP) point at which the first crack occurs. If the load value P_{MOR} corresponding to this point is greater than the P_{LOP} value corresponding to the LOP point where the first crack occurs, it is concluded that the deflection –hardening behavior occurs. If it is less than the P_{LOP} value, the deflection-softening behavior occurs in the specimen subjected to four-point bending. The stress value in the MOR was calculated using Equation (1). In addition, L/600 and L/150 points were determined according to ASTM C1609 [20]. L/600 and L/150 are 1/600 and 1/150 of the test span, respectively. The load and deflection values, toughness and stresses corresponding to the L/600 and L/150 points were calculated. In this study, deflection values at 0.5 mm and 2 mm points were used since the L is 300 mm. While calculating the toughness (T) values, the areas under the load-deflection curves until the L/600 and L/500 points were used. The same P, δ, T and f prefixes were used for the load, deflection, toughness and flexural strength values corresponding to the LOP, MOR, L/600 and L/150 points. The flexural toughness factor (FTF) in N/mm^2 according to JSCE [21] was calculated using Equation (2).

$$FTF = \frac{T_{\left(\frac{L}{150}\right)}.L}{\left(\frac{L}{150}\right).b.h^2} \tag{2}$$

where $T_{(L/150)}$ is the area under the load-deflection curve until 2 mm deflection in N.mm.

3. RESULTS AND DISCUSSION

In this study, PVA and PP synthetic fibers were added into single 1% macro steel FR-SCC specimens and HSFR-SCC specimens having 0.75% macro and 0.25% micro SF to investigate the effects of synthetic fibers on the properties of steel FR-SCC. For this purpose, the fresh, hardened and toughness properties of these designed mixtures were obtained as summarized in Table 4-7.

Table 4. Fresh SCC test results

Mix Code	Unit weight (kg/m^3)	Slump-Flow		J-Ring		
		D_s (mm)	t_{50} (sec)	D_J (mm)	t_{50J} (sec)	ΔH (mm)
Control	2159	770	4	780	4	0.3
MA1	2458	750	5	730	6	4.0
MA1_PVA	2296	710	7	685	10	7.0
MAK_PP	2239	718	6	690	8	6.5
MA0.75_MI0.25	2419	742	5	724	7	3.5
MA0.75_MI0.25_PVA	2368	723	6	698	9	5.0
MA0.75_MI0.25_PP	2353	730	5	700	8	4.7

3.1. Fresh SCC Properties

The fresh properties of designed mixtures were given in Table 4.

3.1.1. Fresh unit weight

Observing Fig. 3, the fresh unit weight values of all FR-SCC mixtures were higher than those of the control mixture due to the fact that they contain SFs. Besides, it was obvious that the addition of synthetic fibers into the single and HSFR-SCC mixtures induced the fresh unit weight values. In addition, the inclusion of PP into the single steel FR-SCC mixtures caused 2.3% more reduction in unit weight with regards to control mixture compared to the one with PVA while that value was 0.6% for the HSFR-SCC mixtures. It may be attributed to the lower specific gravity of synthetic fibers which was used as a replace of aggregates. Moreover, the reason of having lower unit weight of MA1_PVA and MA1_PP than MA0.75_MI0.25_PVA and MA0.75_MI0.25_PP may be due to the use of micro SF at a rate of 0.25% instead of macro SF which increases the packing density of the fibers. The similar finding was also obtained in the study of Kina [27]. Besides, the use of PP fiber decreased the unit weight of the mixtures with regards to that of the PVA fiber. It may be attributed to the fact that the same volume fractions of both fibers caused the use of different amount of fibers since their specific gravities are different from each other.

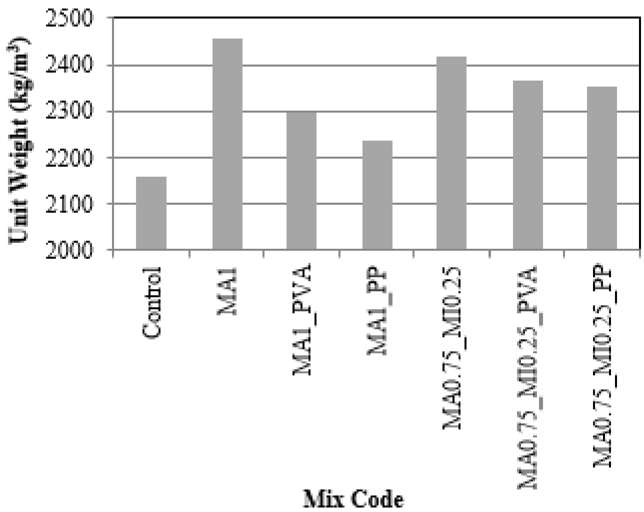


Figure 3. The fresh unit weight values of designed SCC mixtures

3.1.2. Slump-flow diameter and t_{50}

Referring to Fig. 4, the addition of PVA and PP into single SFR and HSFR-SCC caused a decrease in the slump-flow diameter (D_S) values while an increase in t_{50} values occurred. It was observed that PVA had more negative effect on the slump-flow test results than PP fiber. The addition of PVA fiber into single SFR-SCC mixtures caused 1.06% more reduction in slump-flow diameter compared to the one with PP while there was 0.94% decrease in D_S of HSFR-SCC mixture. In the studies of Ahmad and Umar [28] and Zhu et al. [29], it was found that there was a decrease in D_S with the addition of PVA fiber into the concrete. Besides, it was noted that PP synthetic fiber had less negative effect on the workability properties of mixtures. This may be due to the fact that PP fiber disperses more homogeneously and prevents agglomeration. Moreover, it may be also attributed to the hydrophilic nature and having high aspect ratio of PVA which adversely affect the fresh properties of mixtures [30]. In the study of Umar et al [31] the slump values of the SCC with no fiber decreased by 3.97% and 5.56% with the addition of 0.2% PP and 0.2% PVA fibers, respectively. This higher reduction in flowability of PVA fiber reinforced SCC was explained by the poor dispersibility of PVA fiber which's surface texture is relatively less smooth. In the literature, the similar results were also found by the other researchers [29, 32].

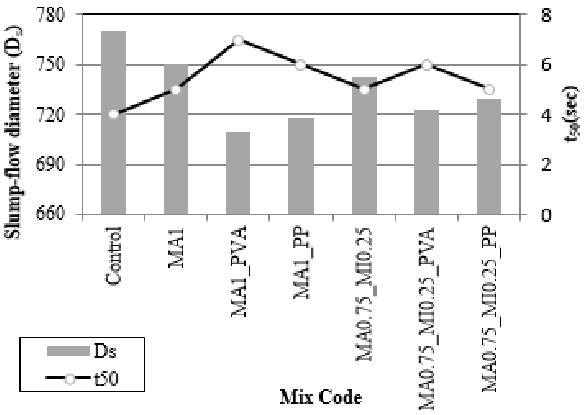
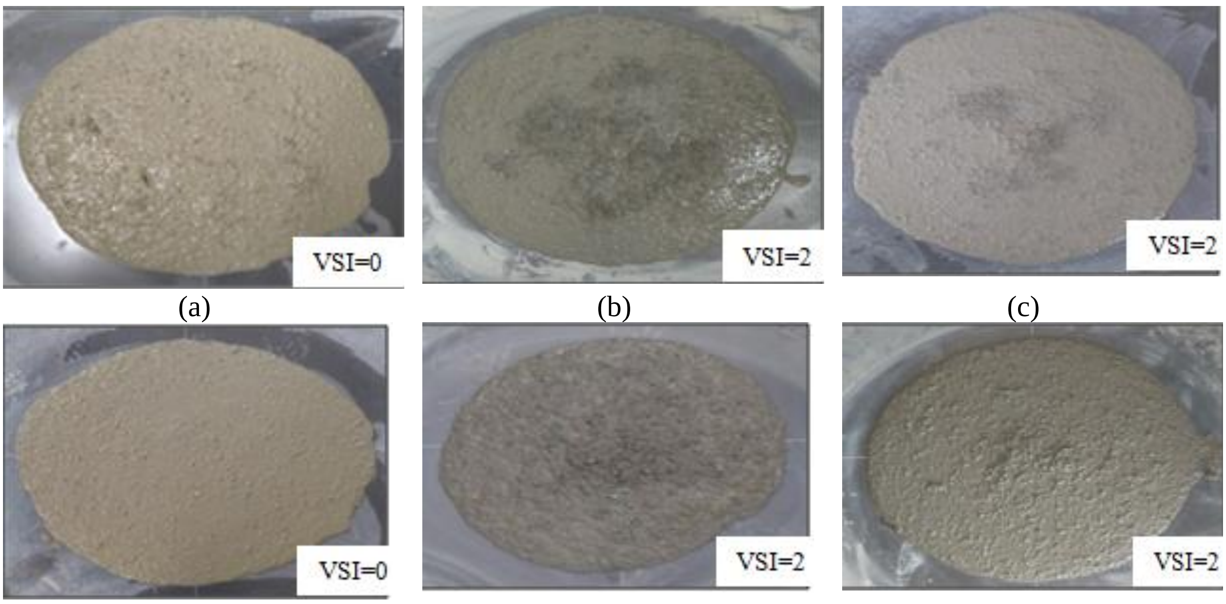


Figure 4. The slump-flow diameter and t_{50} values of designed mixtures

In this study, Visual Stability Index (VSI) values were used to evaluate the stability of FR-SCC mixtures according to ASTM C1611 [33]. When the visuals given in Fig. 5 were examined, it was seen that the VSI value of MA1 and MA0.75_MI0.25 was 0. However, the VSI values of FR-SCC mixtures became 2 by the addition of PVA and PP synthetic fibers into single and HSFR-SCC mixtures. It may be due to the formation of segregation as a result of agglomeration caused by the synthetic fibers. Observing Fig. 5, at the center part of the mixtures having PP and PVA fibers, the agglomeration appeared in the matrix because of the poor dispersion of fibers. Nevertheless, it was found that all the FR-SCC mixtures have acceptable stability.



(a) (b) (c)

(d) (e) (f)

Figure 5. VSI assessments based on slump-flow diameter visuals of (a) MA1, (b) MA1_PVA, (c) MA1_PP, (d) MA0.75_MI0.25, (e) MA0.75_MI0.25_PVA, (f) MA0.75_MI0.25_PP

3.1.3. J-Ring slump-flow diameter, t_{50J} and height difference

Observing Fig. 6, the incorporation of synthetic fibers into single and hybrid SFR-SCC decreased the J-ring slump-flow diameters and increased the t_{50J} values. It was also seen that the use of PVA and PP into the SCC mixtures increased the J-Ring height difference value (ΔH) as in the case of other studies [28, 34]. When synthetic fibers were compared with each other in the J-ring test, it was determined that PVA has a more negative effect than PP fiber. The inclusion of PVA into single steel FR-SCC mixtures caused 0.68% more reduction in DJ compared to the one with PP while 0.27% decrease was observed in D_J of HSFR-SCC mixtures. That is because, PP fiber spreads more homogenously in the mixture compared to PVA and causes less agglomeration. The reason for the decrease in the DJ of the mixtures can be explained by getting stuck of aggregates and macro SFs to the obstacles on the ring, since the SFs and synthetic fibers in the FR-SCC mixture cause agglomeration. As it can be proven by the Fig. 7, in the mixture of MA1_PVA, the agglomeration in the inside part of the J-ring was more obvious than that of the mixture of MA1_PP. The inability of these solid materials in the FR-SCC mixtures to pass between the obstacles causes a height difference (ΔH) in the inner and outer parts of the ring. ΔH values increased with the addition of synthetic fibers into single and HSFR-SCC mixtures.

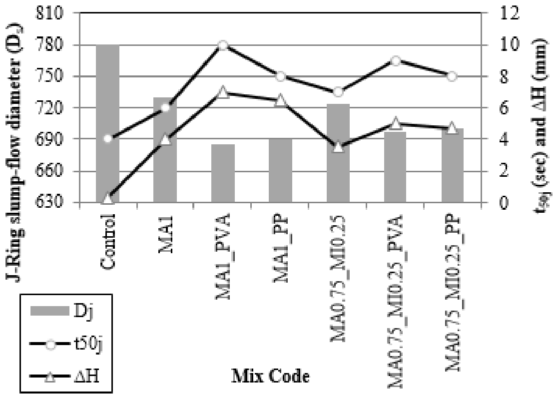


Figure 6. The J-Ring slump-flow diameter, t_{50j} and ΔH values of designed mixtures

Figure 7. The agglomeration of the mixtures (a) MA1_PVAand (b) MA1_PP

3.2. Hardened SCC Properties

The hardened properties of designed mixtures were given in Table 5.

Table 5. Hardened SCC test results

Mix Code	Statistical Values	f_c (MPa)	f_{ct} (MPa)	f_f (MPa)
Control	μ	85.1	3.2	8.3
	σ	1.98	0.07	0.28
MA1	μ	100.4	8.4	12.5
	σ	5.52	0.57	0.13
MA1_PVA	μ	92.4	8.9	20.9
	σ	3.39	0.42	1.24
MA1_PP	μ	87.9	8.8	17.6
	σ	3.11	0.42	0.11
MA0.75_MI0.25	μ	101	8.6	12.4
	σ	2.83	0.28	0.1
MA0.75_MI0.25_PVA	μ	94.9	10.2	16.4
	σ	5.3	1.06	0.13
MA0.75_MI0.25_PP	μ	93.1	10	15.7
	σ	0.42	0.57	0.07

μ : average, σ : standard deviation

3.2.1. Compressive strength

Observing Fig. 8, the use of PVA and PP synthetic fibers into SFR-SCC decreased the f_c values and PVA fiber showed less negative effect on f_c than PP fiber. The addition of PP fiber into single SFR-SCC caused 4.49% more reduction in the f_c values compared to the ones with PVA, while it was seen that it led to a 1.78% decrease in the f_c values of HSFR-SCC. This can be attributed to the inability of the synthetic fibers to be dispersed homogenously in the SCC mixture and to agglomerate due to the low shearing effect of the mixer used in the preparation of the mixtures. In some studies [35–39], it was also determined that the use of PP and PVA fibers into concrete adversely affect the fresh properties of SCC mixtures. Thus, the decrease in the filling rate of the mixtures affected the f_c of concrete negatively.

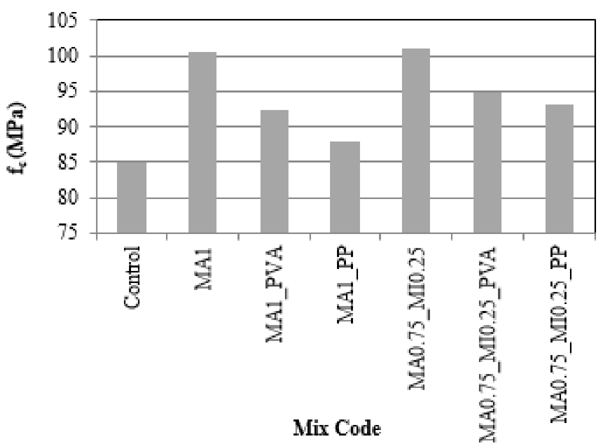


Figure 8. The f_c of designed SCC mixtures

3.2.2. Splitting tensile strength

When the effect of synthetic fibers on the f_{ct} was examined, it was observed that adding PVA and PP separately into the single and HSFR-SCC mixtures increased the f_{ct} (see Fig. 9). Besides, it was found that PVA fiber had more positive effect on the f_{ct} with regards to PP fiber. Addition of PVA into single SFR-SCC caused more enhancements with 1.07% in the f_{ct} compared to the one with PP, while it caused an increase of 1.86% for HSFRC-SCC. This situation can be explained by the fact the use of binary and more fiber hybridization can show superior performance with regards to single fiber and it can be called as synergy. In the literature, some findings obtained by the other researchers [40, 41] also support this situation.

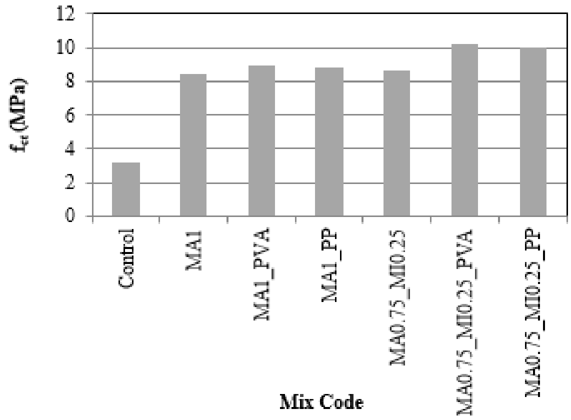


Figure 9. The f_{ct} of designed SCC mixtures

3.2.3. Flexural strength

Observing Fig. 10, when the flexural strengths of SCC specimens were examined, an increase in f_f was observed with the addition of synthetic fiber into SFR-SCC mixtures. Besides, it was observed that PVA fiber had a more positive effect on f_f compared to PP fiber, similar to splitting tensile strength. Addition of PVA fiber into single SFR-SCC caused more increase with 11.21% in f_f compared to the one with PP, while that value was 3.37% for HSFRC-SCC. This is because the use of synthetic fibers can increase the total fiber volume with regards to the SCC mixtures containing only single and hybrid SF [42]. Moreover, the hydrophilic nature of PVA fiber can be shown as the reason of its increase. In the study of Emamjomeh et al [43], the mixtures with PVA fiber also exhibited higher flexural strength compared to those of the ones with PP fiber. This fact was attributed to having higher tensile strength of PVA and higher PVA-matrix bond strength with regards to that of the PP-matrix interface. At the interface of the PVA, both frictional and chemical bonds are at work. However, the lower bond strength of PP-matrix interface is because of the frictional bonding rather than a chemical one [44]. Studies carried out by some researchers [41, 45] found that the inclusion of both PP and PVA fiber into cementitious composites has a positive effect on the f_f. Thus, for this study, it can be concluded that the synergy resulting from the addition of PVA or PP into mixtures as second or third fiber also increases the f_f.

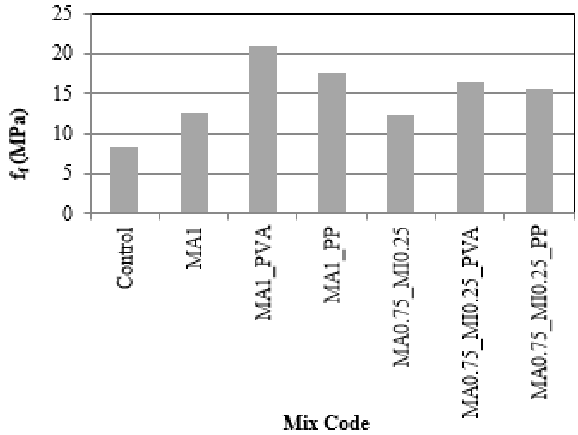


Figure 10. The f_f of designed SCC mixtures

3.2.4. Flexural performance

The flexural performance of designed mixtures was given in Table 6.

3.2.4.1. *Toughness (Energy absorption capacity)*

The flexural strength-mid span deflection curves of all FR-SCC specimens were shown in Fig. 11 and also the values obtained from the test results were given in Table 7. While the control specimen with no fiber showed a brittle fracture, as can be seen in Fig.12(a) and (b), all FR-SCC samples exhibited deflection-hardening behavior. The addition of fibers into SCC prevented brittle fracture and created the deflection-hardening behavior, thus made the concrete behave more ductile. Observing Table 6, when all samples were taken into account, it was seen that the MA1_PVA samples absorbed the most energy, while the MA0.75_MI0.25 samples had the lowest energy absorption capacity. Besides, it was found that the energy absorption capacity of the samples increased with the addition of PVA and PP synthetic fibers into SCC. On the other hand, when the area under the load-deflection curves (energy absorption capacity) of the samples consisting of a binary and ternary fiber hybridization of SF, PVA and PP fibers were examined, it was seen that the use of PVA showed higher enhancement compared to PP fiber. It may be due to the slip-hardening behaviour of PVA fiber [46] which enabled to achieve higher strain capacity. In the study of Khan and Ayub [47], PP fiber reinforced SCC also exhibited lower strain-hardening response after cracking and it was attributed to the weak bond between PP and matrix interface. Similar findings were also obtained by the study of Pakravan et al. [48].

Table 6. The flexural performance of FR-SCC specimens

Mix Code	Energy Absorption Capacity (N.m)	Failure Behavior	Ductility		
			δ_{LOP}	δ_{MOR}	D-index
MA1	72.48	Deflection hardening	0.019	0.347	18.17
MA1_PVA	119.58	Deflection hardening	0.018	0.485	26.8
MA1_PP	102.54	Deflection hardening	0.017	0.431	26.12
MA0.75_MI0.25	72.94	Deflection hardening	0.02	0.269	13.52
MA0.75_MI0.25_PVA	96.44	Deflection hardening	0.017	0.443	25.91
MA0.75_MI0.25_PP	85.01	Deflection hardening	0.022	0.483	22.05

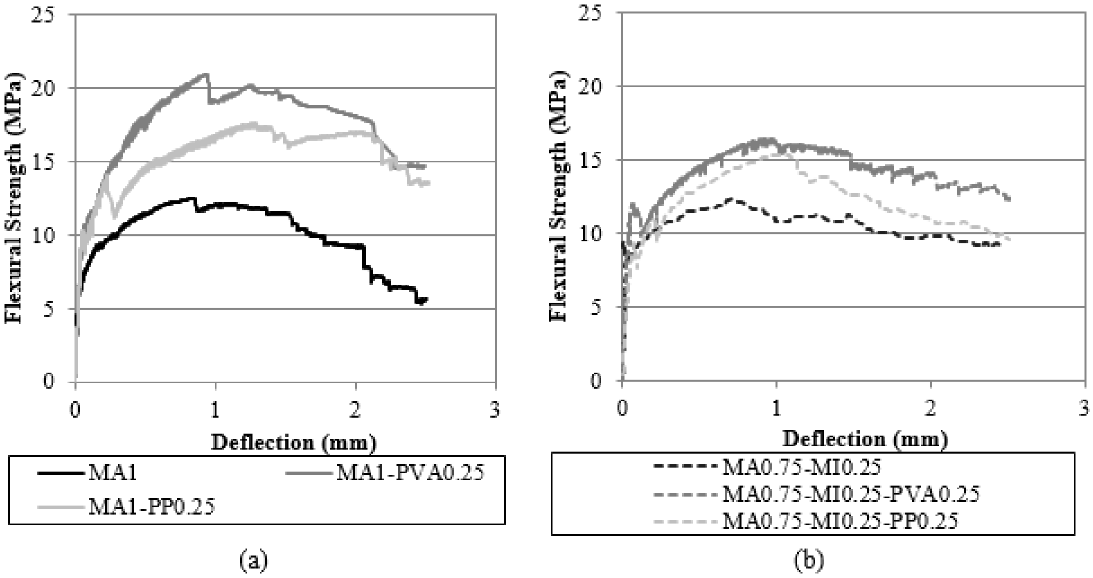


Figure 11. The flexural strength-mid span deflection curves of SFR-SCC samples containing different synthetic fiber: (a) single SFR-SCC, (b) HSFR-SCC

Table 7. The flexural properties of FR-SCC specimens

Mix Code		MA1	MA1_PVA	MA1_PP	MA0.75_MI0.25	MA0.75_MI0.25_PVA	MA0.75_MI0.25_PP
L/600	$\delta_{L/600}$	0.5	0.5	0.5	0.5	0.5	0.5
	$f_{L/600}$	11.42	17.92	14.53	11.62	14.53	13.26
	$T_{L/600}$	15.72	22.95	19.82	17.27	20.06	18.84
L/150	$\delta_{L/150}$	2	2	2	2	2	2
	$f_{L/150}$	9.13	18.05	16.98	9.83	14.03	10.9
	$T_{L/150}$	72.48	119.58	102.54	72.94	96.44	85.01
MOR	δ_{MOR}	0.84	0.93	1.28	0.71	0.93	0.96
	f_{MOR}	12.49	20.96	17.58	12.44	16.27	16.35
	T_{MOR}	29.42	50.98	62.26	26.25	33.52	44.17

The effect of the addition of synthetic fiber into SFR-SCC mixtures on the load carrying capacity was shown in Fig. 12 for different deflection points. Flexural strength values were calculated using Equation (1) for these three different deflection points determined based on [20]. These deflection points are the deflection points corresponding to L/600, L/150 and MOR for ASTM C1609 [20]. When the findings were examined it was seen that the effects of the fibers became more pronounced as the deflection point increased. As seen in Fig. 11, the flexural strength increased for all deflection points by the addition of synthetic fibers into SFRC-SCC and it was observed that the MA1_PVA specimen exhibited the best performance in terms of flexural performance. Moreover, the samples having synthetic fiber showed higher increase in the resistance against the bending load before the peak load than those of the samples with single and hybrid SF. In fact, it was observed that the increase in resistance to bending load of the samples containing PVA fiber was much more pronounced. As a result, when the effect of the addition of synthetic fiber into the single and HSFR-SCC samples on the flexural performance was investigated, it was found that PVA fiber caused a greater increase in flexural strength for all deflection points compared to PP fiber.

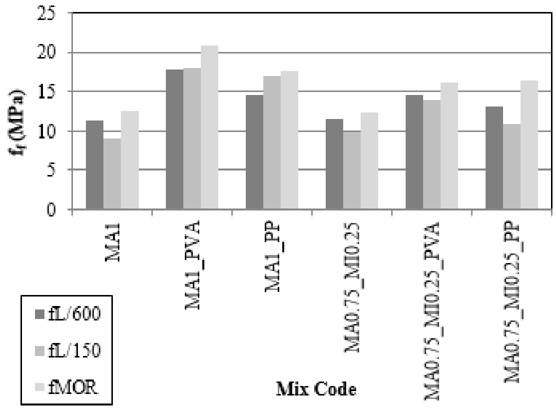


Figure 12. f_f values of FR-SCC samples for some deflection points

3.2.4.2. *Toughness values based on ASTM C1609*

The toughness values of all FR-SCC samples calculated according to ASTM C1609 [20] were given in Fig. 13. In this method, the toughness values at L/600 and L/150 points are taken into account. For this reason, the behavior before and after the peak load in the load-deflection curves could be examined. Observing Fig. 13, the addition of synthetic fibers into single and HSFR-SCC caused an increase in the toughness values. It was determined that the use of PVA as synthetic fiber into SFR-SCC had a more positive effect on toughness values compared to PP fiber.

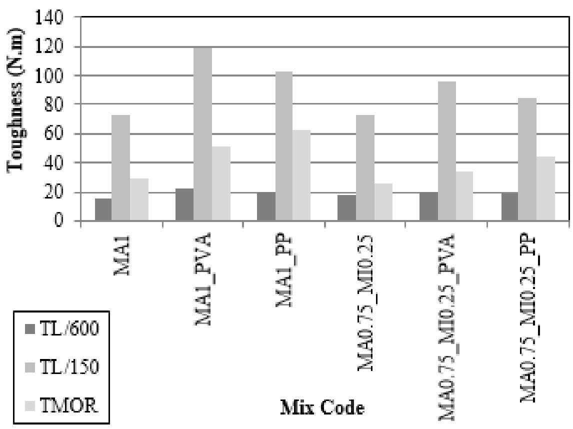


Figure 13. Toughness values of FR-SCC samples for some deflection points

3.2.4.3. *Flexural toughness factors values based on JSCE*

In Fig. 14, flexural toughness factor (FTF) values of all FR-SCC samples were given in order to examine the effect of adding different synthetic fibers into single and HSFR-SCC according to JSCE [21]. Similar to ASTM C1609, the use of synthetic fiber into single and HSFR-SCC caused an increase in the FTF values. When the synthetic fibers were compared among themselves, it was found that the FTF values of the FR-SCC with PVA were higher than the FTF values of the FR-SCC with PP. In this method, only the area under the curve up to the deflection point L/150 was used. Therefore, analysis of the range of load-deflection curves before and after the peak load could not be performed.

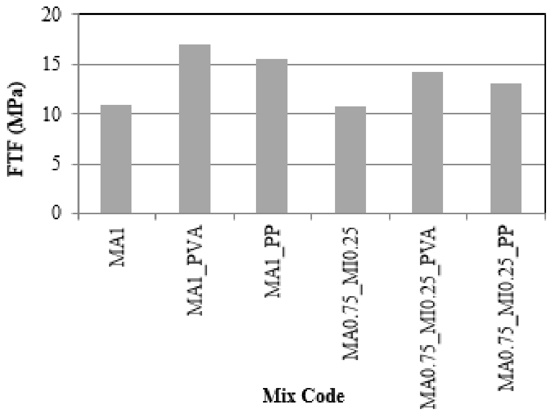


Figure 14. Flexural toughness factor values of FR-SCC samples based on JSCE

3.2.4.4. *Comparison of ASTM C1609 and JSCE*

Considering the above-mentioned results, it was found that the flexural toughness parameters showed similar trends according to both ASTM C1609 and JSCE. However, the important point is to determine which method is suitable for evaluating the flexural performance of fiber reinforced cement based composites. In the ASTM C1609 [20] method, the effect of fiber on the behavior of FR-SCC samples before and after the peak load on the load-deflection curves were determined and also, the flexural strengths of the samples could be calculated. On the other hand, the FTF in JSCE method is only related to the linear function of $T_{L/150}$ [49]. Therefore, the FTF according to JSCE [21] is calculated based on the area under the load-deflection curve up to the specified deflection (L/150=2). In this regard, it was considered that the effect of fiber on the pre-peak load behavior of FR-SCC samples on the load-deflection curve using the JSCE method is insufficient.

3.2.4.5. *Ductility*

The deflection capacity obtained from the four-point bending tests of the samples produced from FR-SCC mixtures is an important parameter in terms of ductility. The ductility index (D-index) values of the SFR-SCC specimens containing different synthetic fibers were shown in Table 6 and Fig. 15. In this study, the ductility index was calculated by Equation (3) as follows;

$$D - index = \frac{\delta_{\mathrm{MOR}}}{\delta_{LOP}} \tag{3}$$

Observing Fig. 15, the highest and lowest D-index values were obtained from MA1_PVA with 26.80 and MA0.75_MI0.25 with 13.52, respectively. However, D-index increased with the addition of synthetic fibers into SCC mixtures. It was found that the use of PVA into SCC mixtures caused more increase with 2% in the D-index of the single SFR-SCC, while the D-index values of the HSFR-SCC samples increased by 9.1% compared to the addition of PP. For all samples, PVA fiber performed better than PP fiber among synthetic fibers.

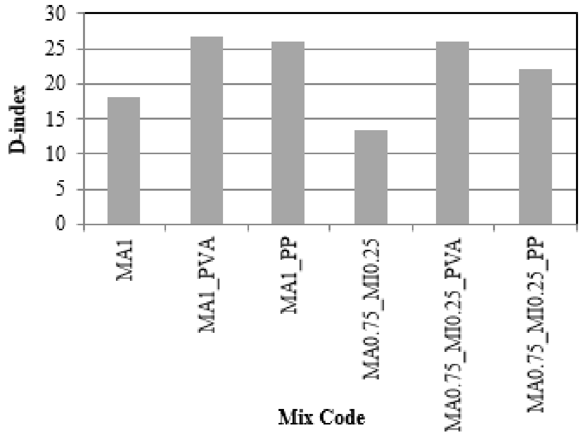


Figure 15. Ductility index values of FR-SCC samples

3.2.4.6 *Crack characterization*

Observing Fig. 16 (a-f), when synthetic fibers were added into SFR-SCC mixtures, a multiple cracking formation was observed due to the branching of cracks. Besides, it was seen that PVA fiber caused more crack branching than PP fiber in the binary and ternary HFR-SCC samples. Large amount of cracks occurred in the mid-span region of the samples due to the branching of cracks resulting in a deflection-hardening behavior [50–53]. It was observed that the use of PVA into single SF-SCC mixtures (MA1_PVA) exhibited highest multiple cracking behavior which is consistent with the energy absorption capacity findings. Another point observed from the bending test was the differences in the crack width on the tension side of the specimens. It was too small in the PVA fiber reinforced SCC specimens while in the PP fiber reinforced SCC specimens, the cracks were larger which could be due to the higher slippage distance of PP fiber. In the study of [43], it was found that the limited slippage distance of PVA fibers might be the main reason underlying the higher energy absorption capacity and crack formation with less width.

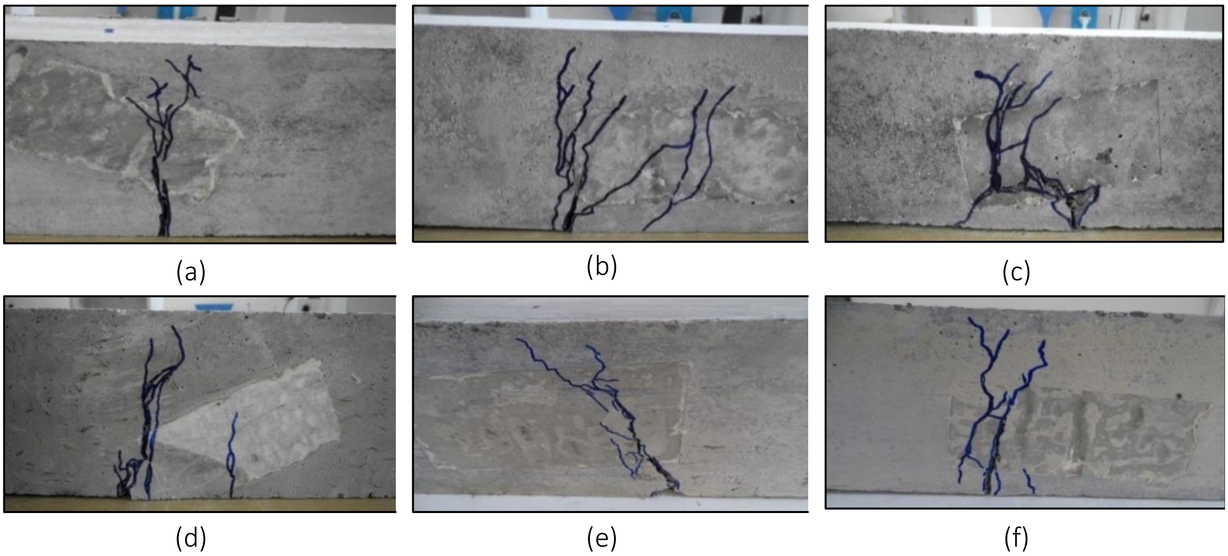


Figure 16. Crack characterization of FR-SCC samples; (a) MA1, (b) MA1_PVA, (c) MA1_PP, (d) MA0.75_MI0.25, (e) MA0.75_MI0.25_PVA, (f) MA0.75_MI0.25_PP

4. CONCLUSION

Considering the results obtained from the experimental studies carried out within the scope of this study, the following conclusions can be reached;

- The addition of PVA or PP into SFR-SCC mixtures negatively affected the fresh properties of SCC. Besides, among synthetic fiber, it was found that PP influenced the workability of SCC less negatively than PVA.
- The use of synthetic fibers into SFR-SCC mixtures reduced the f_c but PVA fiber had less negative effect on f_c compared to PP.
- The splitting tensile and flexural strength of SFR-SCC samples were enhanced by the use of synthetic fiber and it was seen that PVA fiber had more positive effect than PP fiber.
- All SFR-SCC samples showed deflection- hardening behavior. Besides, it was found that the use of synthetic fiber into single (MA1) and HSFR-SCC (MA0.75_MI0.25) samples improved the energy absorption capacity and it was more pronounced in the SFR-SCC samples with PVA.
- It was found that the flexural toughness parameters showed similar trends based on ASTM C1609 and JSCE. The addition of PVA into single SFR-SCC caused the highest enhancement in the toughness values.
- The inclusion of synthetic fibers in SFR-SCC caused more multiple cracking behavior while more pronounced crack branching was observed in the single SFR-SCC containing PVA.

To sum up, it was found that the addition of synthetic fibers improved the flexural strength and performance of the SFR-SCC mixtures to a high extent. Especially, single SFR-SCC samples with PVA showed superior performance. It is obvious that this feature can provide great advantages in structures which are exposed to dynamic loads such as earthquakes as well as external environmental effects such as infrastructure and industry.

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CONFLICT OF INTEREST

The author(s) stated that there are no conflicts of interest regarding the publication of this article.

AUTHORSHIP CONTRIBUTIONS

Ceren Kina: Formal analysis, Writing - original draft, Visualization, Conceptualization. **Esma Balalan:** Formal analysis, Investigation, Conceptualization. **Kazim Turk:** Supervision, Visualization, Conceptualization.

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