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ORIGINAL ARTICLE

Bond strength of reinforcing bars in hybrid fiber-reinforced SCC with binary, ternary and quaternary blends of steel and PVA fibers

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Abstract In this study, the effect of inclusion of single fiber and binary, ternary and quaternary fiber hybridization on the bond performance of high strength self-compacting concrete (SCC) was investigated and 12 beam specimens having lap-spliced reinforcing bars in tension at the mid-span were designed. Four different fibers were used with different hybridizations. Fiber reinforced concrete beams demonstrated higher failure loads with a greater number of cracks. Especially the specimens with ternary fiber hybridization showed the best performance that the ultimate load resistance was 60% higher than that of the specimen without fiber. After splitting failure, the beam specimens with binary hybridization of macro steel fiber and polyvinyl-alcohol (PVA) fiber and also, the specimens with ternary hybridization of macro steel fiber, micro steel fiber with 13 mm in length (OL 13/.16) and PVA fiber showed a gradually drop in performance with increasing deflections. Besides, results indicate that the least improvement in bond strength was observed in the specimen having quaternary fiber hybridization of macro steel fiber, OL 13/.16 and micro steel fiber with 6 mm in length (OL 6/.16) and PVA fiber. The bond strength results were also compared with the ones calculated from the existing prediction equations. It was found that Zuo and Darwin and Esfahani and Rangan equations gave better results than the equations of Orangun et al. and ACI 318 on the hybrid fiber reinforced SCC. Based on the results, it was indicated that in these proposals, a new parameter was necessary for the fiber content so in this study, a new empirical equation was derived by using fiber reinforced index for fiber reinforced SCC. The proposed equation gave better estimation in the specimens with single fiber and binary and ternary fiber hybridization.

Keywords Hybrid fiber · Bond strength · Tension lap splice · Ductility · Estimation

Abbreviations

α	Reinforcement location factor
A_s	Area of steel bar
β	Coating factor
c	Neutral axis depth
c_1 and c_2	Coefficients obtained from the regression analysis
c_{max}	Maximum of c_x, c_y and $c_s/2$
c_{med}	Median of c_x, c_y and $(c_s + d_b)/2$
c_{min}	Minimum of c_x, c_y and c_s/s
c_s	Clear spacing between the splices

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c_x	Spacing between the bars
c_y	Bottom cover
δ	Mid-span deflection
d_b	Diameter of tension reinforcement
d_f	Diameter of fiber
FA	Fly ash
f'_c	Compressive strength of concrete
f'_s	Stress of tension reinforcement
γ	Reinforcement size factor
λ’	Lightweight aggregate concrete factor
λ (FR-I)	Fiber reinforced index
l_d	Splice length
L_f	Length of fiber
PC	Portland cement
P_{max}	Failure load
RMSE	Root mean square error
σ_α	Yield strength of steel bar
σ_c	Tensile strength of steel bar
SF	Silica fume
u	Bond strength
u_c	Local bond strength
u_{test}	Measured bond strength
V_f	Fiber content by volume

1 Introduction

The addition of supplementary cementitious materials can increase the brittleness of high strength concrete and to cope with this deficiency, in recent decades, fibers have been used [1, 2]. Fibers enhance the tensile characteristics of concrete by preventing the crack initiation and growth. Due to these advantageous properties of fibers, the application of fiber-reinforced SCC has been increasing its popularity throughout the world. For example, the addition of fibers into SCC has been widely used in the areas of infrastructure and industrial applications such as industrial floors, airport pavement, channel lining and overlays because fibers cause an improvement in the durability of concrete compared to plain concrete [3]. Besides, for the precast tunnel lining segmental units [4] in which the control of crack propagation is vital, the fiber-reinforced SCC can also be used. The other applications are related to the use of steel rebars and fibers in a hybrid system. The localized stresses in concrete are resisted by the reinforcing bars while the fibers control the distributed stresses. In the case of having both distributed and localized stresses, this hybrid system can offer an optimal solution [5]. It can be said clearly from these researches that innovative materials such as hybrid fiber reinforced composites and SCC etc. have a great importance to increase the service life of buildings and improve infrastructure and industrial applications.

Different types of fibers such as steel, polyvinyl alcohol (PVA), polypropylene (PP), polyethylene (PE) etc. have been used in concrete and there are lots of studies related with fiber reinforced concrete in the literature [6–13]. In the study of Hossain et al. [6], the fresh, strength and fracture energy characteristics of fiber reinforced SCC mixtures incorporating PVA, metallic fibers and the hybridization of two of them were investigated. It was found from this study that these characteristics were not only depend on the contents, types and size of the fibres but also on the synergy and interaction between fiber types. Turk et al. [7] studied the effects of hybridization of micro and macro steel fibers on fresh and hardened properties of SCC. It was concluded that the addition of only 1% macro steel fiber or 0.75% macro steel fiber with 0.25% micro steel fiber caused a rather plastic behaviour compared to those of the other SCC specimens having less content of macro steel fiber. Khed et al. [8] conducted a study about the fresh and hardened properties of cementitious composites having steel fibers in the form of Tirewire and PVA as hybrid. They reported that Tirewire fibers improved and gained stability in the direct tensile strength while PVA fiber enhanced strain capacity and toughness. Therefore, it was emphasized that the hybridization of fibers caused a synergy for the development of tensile performance of cementitious composites. Pakravan and Ozbakkaloglu [9] reviewed the effects of PP, PVA and PE fibers on the mechanical, durability and physical properties of cementitious composites. They concluded that the fiber type affects the mechanical properties of composites significantly while these fibers have not an important effect on the workability and permeability. Li et al. [10] investigated the impact resistance of steel fiber reinforced SCC and they found that the inclusion of 1% steel fiber into SCC was enough for both good workability and improved impact resistance. According to the review provided by Pakravan et al. [11] about the development of hybrid fiber reinforced concrete, the inclusion of fibers into concrete as hybrid improves the engineering properties such as energy absorption capacity, durability and toughness compared to single fiber reinforcement. Hossain and Manzur [12] compared the shear performance of full depth beams consisting of either ECC or SCC and hybrid composite beams with two different layers of SCC and ECC together. Finally, it was found that the hybrid composite beams showed superior structural performance in terms of energy absorption, shear crack load and load–deflection response compared to conventional SCC beams. Besides, it was emphasized that the shear resistance of the beams was not affected by the ECC to SCC depth ratio significantly. Xie et al. [13] reviewed the factors that affect the fracture properties of fiber-reinforced cementitious composites. They reported that among all types of fibers, steel fiber had the best fracture properties. On the other hand, the inclusion of fibers into cement based-materials as hybrid can enhance the crack resistance as well as the initial fracture toughness. As can be seen from literature review above, the use of fibers (synthetic and/or steel) as hybrid improved the mechanical and durability properties of cementitious composites as well as the shear performance and toughness of bending elements.

Bond mechanism between reinforcing bars and the surrounding concrete is consisted of the friction forces and mechanical interlock between the ribs of reinforcing bar and the surrounding concrete as well as the chemical adhesion. Mechanical interlock is the most predominant one [14–16]. In the reinforced concrete structures' design, adequate bond between the reinforcing bars and concrete in splice length suggested in code provisions [15, 17] is a crucial requirement. Therefore, in the evaluation of bond characteristics, lap-spliced reinforcing bars is an accurate choice in terms of experimental set-up and also in order to establish the design codes [15, 18], it forms the most of data obtained from experiments. On the other hand, due to the insufficient bond strength, the effective beam action, which means the withstanding of tension stresses by adequate bonding, cannot be achieved and thus, the specified design equation become invalid. At the depth of reinforcement, the loss of strain compatibility causes a redistribution of stresses which results in excessive service deflections [14].

Two types of bond failure which are pull-out failure and splitting failure can occur in the reinforced concrete member. In the pull-out failure, between the bar ribs, the concrete was crushed due to the compression. In the splitting failure, the radial tension stresses around the reinforcing bars causes splitting cracks [15]. It is the desired type of bond failure in most concrete members [16, 19].

The bond strength is affected by different factors such as fiber content, transverse reinforcement, bar geometry and diameter, compressive and tensile strength, concrete cover, loading condition, mineral additions in concrete, etc. [20–24]. In the studies of Hamad et al. [25] and Harajli et al. [26], the influence of the steel fiber reinforcement on the bond strength between the reinforcing bar and concrete were investigated. Harajli et al. [26] found that the use of hooked end steel fibers up to 2% increased the bond strength up to 55% which was greater than the contribution of transverse reinforcement with 3 $\sqrt{f'_c}$. Besides, it was observed that the crack width decreased accompanied by an increase in the number of cracks as result of ductile failure as well as the increase in residual load carrying capacity after failure. Besides, Mohebi et al. [27] studied the influence of polypropylene fiber on bond performance and they reported that the addition of 0.15% of polypropylene fiber content caused an 12% improvement in the ultimate load resistance of the specimens. However, after splitting failure this fiber did not provide a residual capacity. Based on the works mentioned above, it can be addressed that the inclusion of fibers into concrete as hybrid would make a greater contribution on the development of bond strength.

2 Research significance

There are lots of studies related with the influence of different types of fibers (such as steel and polypropylene fibers) on the bond performance of reinforcing bars in concrete [19, 25–27]. However, there are no any experimental works carried out to investigate and compare the effects of inclusion of single fiber and binary, ternary and quaternary fiber hybridization on the bond performance of self-compacting concrete. In this study, large-scale lap-spliced reinforced beams, which were produced from hybrid fiber reinforced SCC with different combinations of fibers, were tested under four-point bending.

The aim of this research is to dissipate the lack of reliable experimental data and also give different point of view to the literature about the effect of different type (steel and synthetic), size (macro and micro) and fiber hybridization (binary, ternary and quaternary) on the bond behavior of lap-spliced reinforced SCC beams. In this study, the measured bond strength values for each SCC beams were compared with the other predicted bond strength equations proposed by other researchers [28–31] by using bond efficiency ratio. Though some of the results calculated from the predicted equations were compatible with the bond strength values obtained from experiments, there was a necessity to introduce a parameter related with the volume (V_f) and the aspect ratio (L_f/d_f) of fibers added into SCC mixtures. For this purpose, in this study, by using the statistical analysis, a new empirical formulation was derived for the prediction of bond strength of concrete reinforced with fiber hybridization by introducing the fiber- reinforced index parameter (FR-Index) consisted of the multiplication of the volume and the aspect ratio of fiber $\left(\frac{V_f L_f}{d_f}\right)$. Due to the reason that there was no any proposed equation to analyze the bond behavior of the single and hybrid fiber reinforced SCC, this research work would enlighten on the studies in this field.

3 Experimental program

3.1 Material properties

In all mixtures, standard CEM I 42.5R Portland Cement (PC), F-Class fly ash (FA) and silica fume (SF) were used as binder and their chemical compositions are presented in Table 1. The values of specific gravity for PC, FA and SF were determined as 3.15, 2.45 and 2.2 g/cm^3, respectively.

The fine (0–4 mm) and coarse (4–16 mm) aggregates were grouped and used in the mixtures separately to ensure the self-compacting ability of concrete. The specific gravity and water absorption capacity of fine aggregates were 2.41 g/cm^3 and 2.2%, respectively. The coarse aggregates with maximum aggregate size of 16 mm had 2.67 g/cm^3 specific gravity and 1% water absorption capacity. Besides, the fineness modulus of aggregates was 4.36. In all mixtures, modified polycarboxylic polymer-based HRWA with the specific gravity of 1.08 was used.

A macro steel fiber and three different micro fiber types were used in this study. As micro fiber, two micro steel fibers with different aspect ratio and a micro synthetic fiber (PVA) were selected. A double hooked-end macro steel fiber was named as 5D 65/60. The aspect ratio of straight micro steel fiber was 87 for OL 13/0.16 and 40 for OL 6/0.16. The physical and

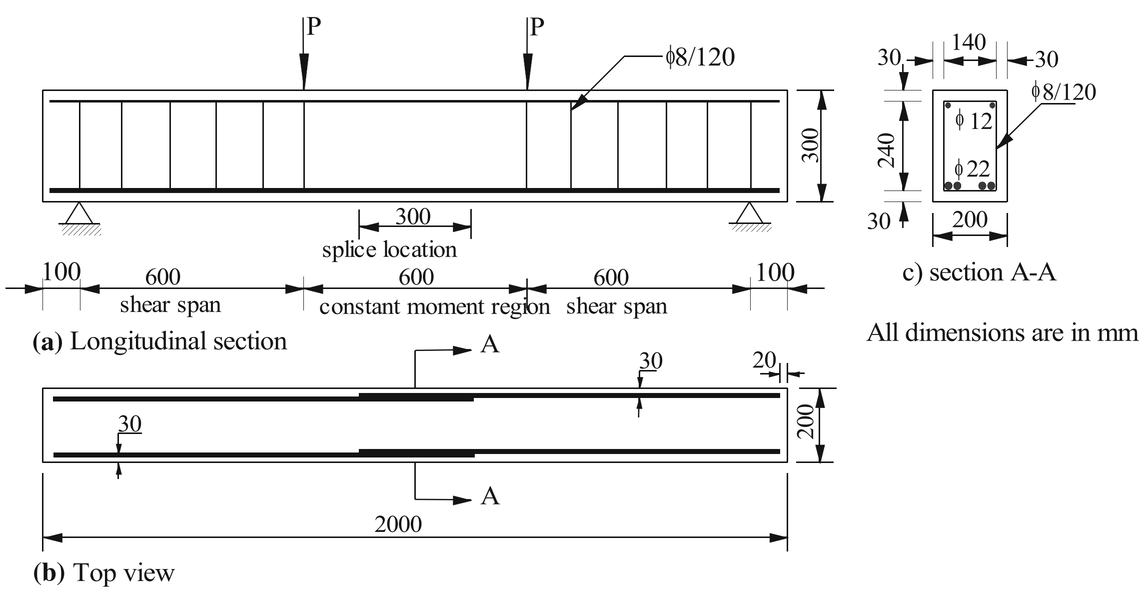


Fig. 1 Longitudinal and cross-sectional details of the test specimen and loading position

Table 1 The chemical compositions of PC, FA and SF

(%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	MnO	P_2O_5	TiO_2	SrO	LOI
PC	19.41	5.58	3.67	58.85	2.12	3.16	0.69	0.61	–	–	–	–	6.07
FA	63.09	3.74	6.11	6.75	10.53	0.63	5.63	–		1.43	1.62	0.2	2.6
SF	94.17	–	1.01	–	1.8	0.19	1.67	–	0.11	–	–	–	1.81

mechanical properties of these four fibers used in this study were presented in Table 2

3.2 Mixture proportions

In this study, five fiber reinforced SCC mixtures and one control mixture having no fiber were designed. In Table 3, the mixture proportions used were presented. The mixtures were reinforced with binary, ternary and quaternary fiber hybridization except for one included only 5D 65/60 macro steel fiber. Among mixtures having binary fiber hybridization, as well as macro steel fiber, one of them included PVA micro synthetic fiber and the other one had OL 13/0.16 micro steel fiber. The mixture having ternary fiber hybridization contained both OL 13/0.16 and PVA micro fibers as well as macro steel fiber. In the mixture reinforced with quaternary fiber hybridization, as well as macro steel fiber, three types of micro fibers (OL 13/0.16, OL 6/0.16 and PVA) were included into mixture. Except control mixture, in all mixtures, the total steel fiber content was kept constant as 1% by volume. However, in the case of having micro steel fiber, the percentage of the macro steel fiber was decreased from 1% to 0.8%. In three mixtures containing PVA micro synthetic fiber, the percentage of PVA by volume was selected as 0.5%. As can be seen in Table 3, in Mix Code, MA, 13MI, 6MI and P symbolized macro steel fiber with 60 mm in length, micro steel fiber with 13 mm in length (OL 13/0.16), micro steel fiber with 6 mm in length (OL6/0.16) and PVA synthetic fiber, respectively, while the control mixture without fiber was named as SCC. Moreover, the numbers written next to the fiber names were the inclusion percentages of the fibers by volume into mixture. The inclusion percentage of PVA was constant for the mixtures, therefore, no number was written next to P abbreviation.

In order to investigate the influence of fiber hybridization on the bond strength of reinforcing bars, the combinations of different type and size of fibers were used and the other proportions of ingredients were kept constant for all mixtures. As binders, PC, FA and SF were arranged as 550, 250 and 50 kg/m^3. To ensure the self-compacting ability of fiber reinforced concrete mixtures, high–volume cementitious materials with 850 kg/m^3 were included to all mixtures and also the ratio of coarse aggregate-to-total aggregate was selected as 0.35. To adjust the similar workability properties for all mixtures, HRWA was used as variable.

Table 2 Properties of fibers

Fibers	Type	Length (mm)	Aspect ratio	Tensile strength (MPa)	Modulus of elasticity (GPa)	Specific gravity (g/cm^3)
5D 65/60	Macro steel fiber	60	65	2300	210	7.8
OL 13/.16	Micro steel fiber	13	87	3000	200	7.2
OL 6/.16	Micro steel fiber	6	40	3000	200	7.2
PVA	Micro synthetic fiber	18	90	1000	27	1.3

Table 3 Mixture proportions (kg/m^3)

Mix Code	Binders			Aggregates		HRWA	Water	Fibers			
	PC	FA	SF	0–4 mm	4–16 mm			5D 65/60	OL 13/.16	OL 6/.16	PVA
SCC	550	250	50	719	347	24	216	–	–	–	–
MA1	550	250	50	699	338	22	217	80	–	–	–
MA1-P	550	250	50	689	333	22	217	80	–	–	6.5
MA0.8-13MI0.2	550	250	50	697	337	23	217	64	16	–	–
MA0.8-13MI0.2-P	550	250	50	681	329	26	218	64	16	–	6.5
MA0.8-13MI0.1-6MI0.1-P	550	250	50	686	331	25	218	64	8	8	6.5

The mixtures were prepared by using the concrete mixer having the capacity of 350 L. At first, fine and coarse aggregates, macro steel fiber and 2/3 of total mixing water were mixed during 3 min. Meanwhile, in the mixtures including micro steel fiber (OL 13/0.16 and OL 6/0.16), these fibers were added into the concrete mixer little by little to provide uniform distribution. Then, the binders (PC, FA and SF) and HRWA, which was solved in the rest of the water, were added to mixture and mixed in total of 10 min. Lastly, PVA fiber was added into the mixtures little by little to prevent the bundling of fiber when the ingredients were dispersed effectively and the mixture in the mixer reached the flowability. To adjust the workability of SCC with fibers, slump flow and t_{50} tests were performed and ΔH values were found through J-ring test. The values of slump-flow diameter were in the range of 675 and 760 mm which satisfied EFNARC criteria (650 and 800 mm) while t_{50} test values between 5 and 10 s. did not conform with the limit values of this standard (2 and 5 s.) due to including fibers into mixtures. Moreover, ΔH results obtained from J-ring test in general ensured the criteria though EFNARC [32] recommendations (0–10 mm) involve the plain SCC except the mixture of MA0.8-13MI0.2-P which was 20 mm.

For each mixture, two large-scale beams having lap-spliced tension reinforcing bars were cast and demolded after 24 h. Then, these specimens were wrapped with wet burlap and covered with plastic nylon for 90 curing days. In order to measure the compressive strength of the mixtures, the prepared cubes were also cured with beam specimens under the same conditions.

3.3 Large-scale beam test specimens

Figure 1 show the details of reinforcing steel bars and beam specimens. For each mixture, two specimens were cast and tested under four-point bending. All specimens had 2000 mm span length with a rectangular cross section of 200 × 300 mm. On the tension side, there are two reinforcing bars having size of 22 mm spliced at the center of the span. The reinforcement details of the beams having lap-spliced reinforcing bars were the same for all mixtures and the laps were located in the constant moment region with a length of 300 mm. No transverse reinforcement was used in the splice location in order to allow a random crack formation. On compression side, the reinforcing bars having size of 12 mm were used and in shear span, transverse reinforcement having the diameter of 8 mm was required to avoid shear failure. The compressive strength of the mixtures used in production of large-scale beams were evaluated according to ASTM C39 [33] by using cube specimens with a dimension of 100 × 100 × 100 mm^3. For each mixture, three specimens were cast and tested. As for reinforcing bars, tensile tests were conducted on tension and compression reinforcements and the obtained results were shown in Table 4. The modulus

Table 4 Information of reinforcing steel bars used

Type of reinforcement	Diameter, ϕ (mm)	Area, A_s (mm^2)	Yield strength, σ_a (MPa)	Tensile strength, σ_c (MPa)
Compression	12	113.1	477.4	631.6
Tension	22	380.1	497.4	702.2

of elasticity of the reinforcements was used as 200 GPa.

The distance between two applied concentrated loads was selected as 600 mm. This design ensured a constant moment region in order to allow random formation of cracks outside the splice location.

The splice length of tension reinforcement was selected to ensure a splitting mode of failure before developing a yielding of steel in all specimens. Because, the bond strength of reinforcing bars cannot be examined in a yielding mode of failure. Due to the reason that the objective of this study was to investigate the influence of hybrid fiber reinforced SCC on the bond strength of reinforcing bar, the reinforcing steel bars must not yield.

3.4 Test set-up and instrumentation

The loading of four-point positive bending was carried out for all specimens.. Rigid steel plate was placed on the beams with 1800 mm clear span and simply supported to distribute the applied loads equally. Loading was applied under displacement control of 1.2 mm/min by means of a feedback-controlled system until failure. In order to measure the mid-span deflection, linear voltage differential transformers (LVDTs) were placed at the center of the beam. An automatic computer aided data logger system was used to monitor mid-span deflection and load. The test duration of large-scale beam specimens produced from SCC having no fiber was approximately 15 min while test durations for the other beams produced from fiber reinforced SCC were in the range of 15 and 20 min due to different fiber hybridization. When the test finished, the crack patterns were marked before unloading so that especially, the micro cracks was observed more apparently.

4 Results and discussions

4.1 Mode of failure

In all beam specimens, the first flexural cracks were observed on the tension side of the constant moment region outside the splice length. By the increase in loading, the cracks formed along the constant moment region including the splice location. In the beams without fibers, the longitudinal cracks formed at the bottom part of the tension side of the splice region and just after the formation of these splitting cracks, the failure occurred. As can be seen in Fig. 2, the bottom concrete cover of the splice region cracked completely. The failure was so brittle, noisy and sudden. However, in the beams having fibers, failure occurred gradually and more ductile that it was also proven by the load–deflection curves in the part of Sect. 3.2. It can be emphasized from here that inclusion of fibers into concrete induced an increase in residual load carrying capacity after failure as well as ductile behavior. During earthquake, this condition had great importance to prevent the formation of plastic hinges at the column ends.

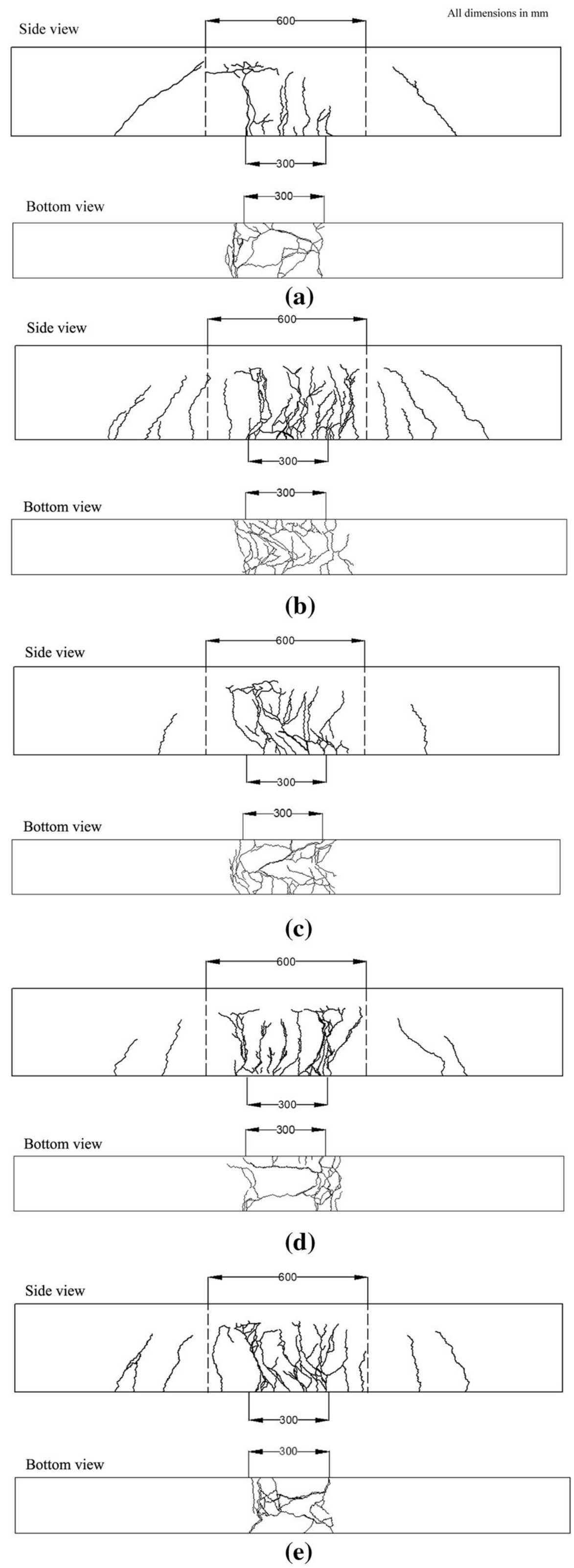
Fig. 2 The beam specimen with no fiber after failure

In the beam specimens reinforced with fibers, it was observed that the width and propagation of flexural cracks were larger and apparent, respectively, in the splice region compared to those of the flexural cracks observed in the outside of splice region. The reason could be due to the fact that before failure, the stress occurred in the splice region was less than the capacity of the reinforcement in that region. In the spliced region, two times of the tension reinforcements were placed compared to the outside part of the spliced region. And thus, it could be said that in the spliced region the load carrying capacity increased. The failure of the beam specimens with fibers were gradually and in a ductile manner, especially for the beam specimens reinforced with binary hybridization of macro steel fiber and PVA micro fiber (MA1-P) and ternary fiber hybridization of macro steel fiber, OL 13/16 micro steel fiber and PVA micro fiber (MA0.8-13MI0.2-P). This condition was also proven by the higher amount of multiple micro-cracks of these specimens under flexural loading as can be seen in Fig. 3. Moreover, in the splice region, the fibers permitted most ribs to promote the transfer of the stress between the lap-splice reinforcing bars and surrounding concrete due to increasing the adhesion of steel bar and concrete. Because, as result of fiber hybridization, as well as the bridging of macro cracks by macro fibers in the splice location, micro fibers bridged micro cracks and delayed the formation and propagation of flexural cracks. Thus, the beam specimens mentioned above demonstrated higher deflections at the failure stage and after failure, the integrity of the specimens was not lost in contrast to the specimens with no fiber. The similar results were also obtained by Hamad et al. [25] who found that increase in steel fiber content in the splice region caused a more ductile and gradual failure mode.

4.2 Load–deflection behavior

The load–deflection response of beams with different fiber hybridization was compared with the response of the SCC beams with no fibers. The load–deflection curves were presented in Fig. 4. Before first cracking, all beam specimens exhibited similar behavior. However, it can be said that the fiber reinforced SCC beam specimens had higher first cracking loads than that of the one including no fibers.

As shown in Fig. 4, a typical behavior of brittle material was observed in SCC specimens with no fiber. The pre-peak part of the load–deflection curve was almost linear and in the post-peak part, in a rapid manner, the load decreased with the increase in deflection. Thus, the specimen lost its load carrying capacity completely. Furthermore, the SCC specimens without fiber had lower failure load and mid-span deflection corresponding to failure load compared to fiber reinforced SCC beam specimens. All fiber-reinforced beams failed within the range of 182 to 241 kN while in the SCC specimens without fiber, the failure load was 149.9 kN. Besides, as can be clearly seen from Fig. 5, compared to the specimen with no fiber, the ternary fiber hybridization (MA0.8-13MI0.2-P) caused the highest improvement with 60.6% in ultimate load resistance of SCC beam specimens. On the other hand, the lowest increase in ultimate load was calculated as 26% for the SCC beam specimens reinforced with quaternary fiber hybridization (MA0.8–13MI0.1–6MI0.1–P).



◀**Fig. 3** Crack patterns of beam specimens reinforced with fibers; **a** MA1, **b** MA1-P, **c** MA0.8–13MI0.2, **d** MA0.8–13MI0.2–P, **e** MA0.8–13MI0.1–6MI0.1–P

After ultimate load, the SCC beam specimens with fibers did not experience a complete loss of load resistance and showed ductile behavior. The reason of this behavior could be attributed to the bridging mechanism of cracks by the fibers during flexural loading. Because, the fibers improve the tensile characteristics of concrete by reducing the width of cracks. Also, this could be due to the fact that the use of hybrid fiber could increase the adhesion between the slipped reinforcement and the surrounding concrete by allowing more lugs to promote the stress transfer as result of the synergy of fiber hybridization. In conclusion, it can be addressed that as well as bond performance of reinforcing bar, improvement in concrete tension by fiber hybridization also ensured an advantage in terms of the areas of infrastructure and industrial applications because of an improvement in the durability properties of concrete. In the literature, the similar results were also obtained by the other researchers [25, 34, 35] who found that when fiber volume increased, the adhesion between the lap-spliced bars and concrete improved because of bridging the cracked surface by fibers after cracking as result of improving the tension resistance.

It was obvious from the Fig. 4 that after ultimate load, the beam specimens having binary and ternary fiber hybridization with PVA fiber (MA1–P and MA0.8–13MI0.2–P) showed a gradually drop in flexural performance with increasing in mid-span deflections. Also, the higher amount of multiple micro-cracks observed in these beam specimens. The reason of such ductile behavior could be due to the advantageous properties of PVA fiber because the modulus of elasticity of PVA with 27 GPa was lower than those of steel fibers (see Table 2). In the studies of Toutanji et al. [36] about the investigation of the properties of high-performance organic aggregate cementitious material with PVA, they also found that PVA fiber ensured better elongation and load transmission between different parts of the matrix by distributing the applied load more uniformly. Besides, the strong bond was achieved between the cementitious matrix and PVA fibers due to its hydrophilic nature [37]. However, after reaching ultimate load, the other specimens without PVA fiber and with quaternary fiber hybridization (MA1, MA0.8-13MI0.2 and MA0.8-13MI0.1-6MI0.1-P) experienced a sharp loss of load resistance and then the load continued to decrease with increasing in deflection.

4.3 Bond strength

As it was also mentioned in Sect. 2.3.2, a splitting mode of failure was aimed in the large scaled beam

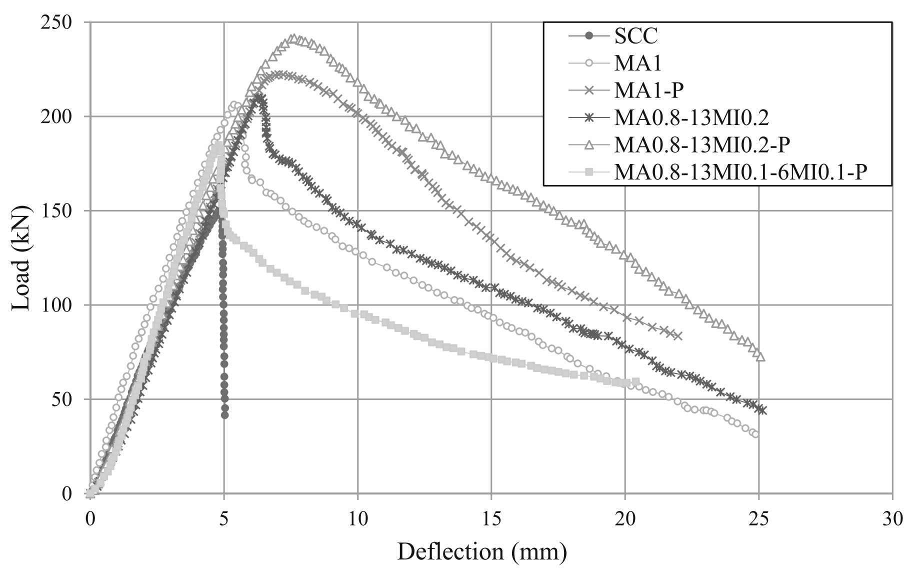


Fig. 4 Load–deflection curves of beam specimens

tests. In this mode of failure, the splice reaches its maximum capacity and the stress developed in the steel could be directly used in order to determine the bond strength. It means that before yielding of steel, failure in concrete occurred. Thus, the bond strength was directly related to the stress in steel, f_s, which was evaluated according to elastic cracked section analysis. The bond stress, u_t, was calculated by using Eq. 1 as follows;

$$u_t = \frac{(A_S f_s)}{\pi d_b l_d} = \frac{f_s d_b}{4 l_d} \quad (1)$$

where A_s, f_s and d_b were the area, stress and diameter of tension reinforcement, respectively and l_d was the splice length.

The results of the large scaled beams reinforced with/out fiber were presented in Table 5. The bond strength values were calculated by using the mean values of two large scaled beam specimens. In this table, f_c was the compressive strength, FR-I was fiber reinforced index, P_{max} was failure load, δ was mid-span deflection and c was the neutral axis depth.

In order to show the influence of fiber hybridization on the bond strength of reinforcing bar, the normalized bond strength values were obtained by dividing the bond strength values of the beam specimens with fiber to the bond strength value of SCC beam specimens with no fiber and presented in Fig. 5. As can be clearly observed from this figure, fiber hybridization improved the bond strength because the bond strength values of all beam specimens with fiber hybridization was higher than that of the one included no fiber. It can be attributed to the fact that the fibers could prevent the initiation and growth of cracks and provide a mechanism increasing energy absorption capacity. In conclusion, it can be emphasized that inclusion of fiber into concrete will cause an efficient bond between reinforcing bars and concrete. As can be seen in Fig. 5, ternary fiber hybridization caused highest improvement in the bond strength of specimens with 65.9% followed by the bond strength of specimens having binary fiber with PVA, binary fiber with 13/0.16 micro steel, single fiber and quaternary fiber compared to that of the specimens without fiber. It was clear from this result that in case of inclusion of hybrid fiber into concrete, the spacing of stirrups in beam-column joint could be decreased to increase the ability of concrete to pass between reinforcing bars and thus, resulting in better bond of steel bars.

When the beam specimens having binary fiber with PVA and binary fiber with 13/0.16 micro steel were compared to each other, it can be noticed that the positive effect of PVA synthetic micro fiber on the bond strength was more evident than that of OL 13/0.16 micro steel fiber. The reason of this result can be explained as follows; the specific gravity of PVA fiber was lower than that of OL 13/0.16 micro steel fiber. Hence, higher amount of PVA fiber was included into the mixture and thus, a greater number of micro cracks could be bridged under flexural loading. In addition to this, the beam specimens having binary fiber with PVA (MA1-P) contained higher ratio of macro steel fiber than the beam specimens having binary fiber with OL 13/0.16 micro steel fiber (MA0.8-13MI0.2). Because, macro steel fiber also had advantages in the improvement of bond strength because of having long and double-hooked end geometric properties as well as higher modulus of elasticity. Harajli and Salloukh [38]found similar result in their study that the use of higher ratio of hooked-end macro steel fiber increased the bond strength in the ratio of 55% with respect to the beam specimens having no fiber.

Table 5 Test results

Mix Code	f_c (MPa)	FR-I	P_{max} (kN)	δ (mm)	c (mm)	f_s (MPa)	u_t (MPa)
SCC	68.3 (1.9)	0	149.9 (4.2)	4.8 (0.1)	26.9 (0.8)	224.2 (7.1)	4.1 (0.1)
MA1	77.0 (1.9)	0.65	206.2 (4.2)	5.2 (0.3)	32.4 (0.6)	312.5 (6.9)	5.7 (0.1)
MA1-P	69.4 (0.4)	1.10	222.2 (2.8)	6.9 (0.1)	34.8 (0.4)	339.3 (4.4)	6.2 (0.1)
MA0.8-13MI0.2	74.6 (3.3)	0.69	209.7 (7.2)	6.1 (0.2)	32.9 (1.0)	318.5 (12.1)	5.8 (0.2)
MA0.8-13MI0.2-P	70.8 (2.9)	1.14	241.2 (3.6)	7.5 (0.1)	36.9 (0.8)	369.5 (6.6)	6.8 (0.1)
MA0.8-13MI0.1-6MI0.1-P	69.3 (1.8)	1.22	182.2 (9.5)	5.4 (0.2)	30.5 (0.6)	278.8 (10.4)	5.1 (0.2)

(The values in bracket () include standard deviation)

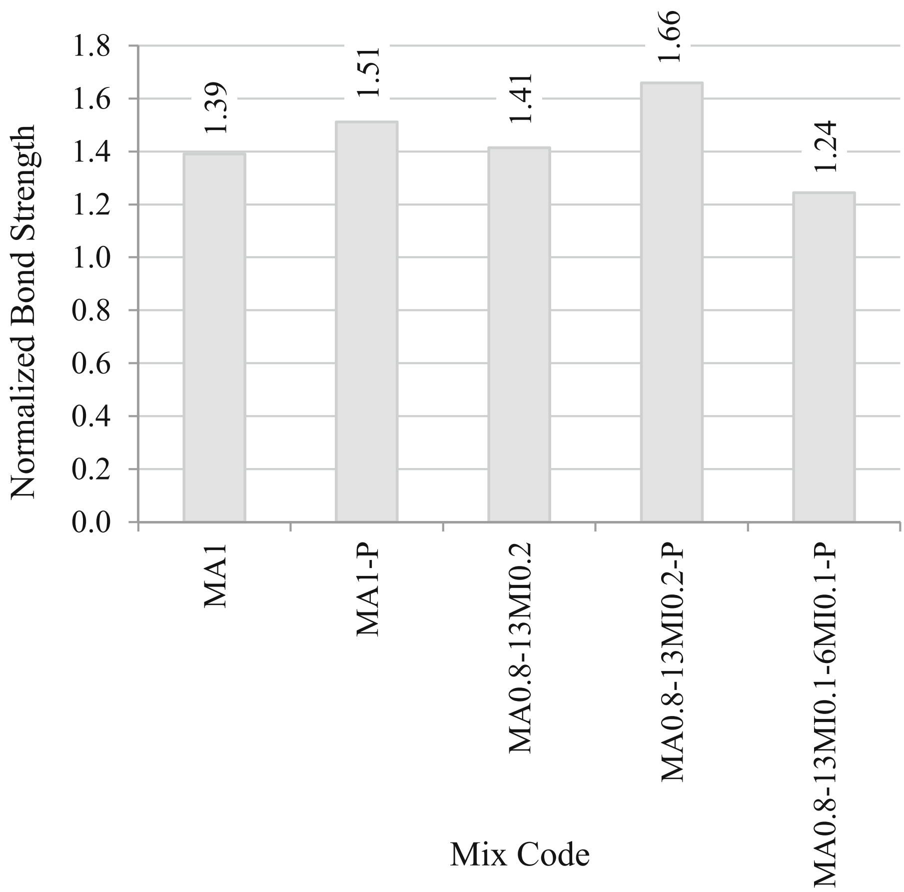


Fig. 5 The normalized bond strengths of the fiber reinforced SCC mixtures with respect to SCC mixture included no fiber

The bond strength of the beam specimens with ternary fiber hybridization was calculated as the highest one with 6.8 MPa in all SCC beam specimens due to providing more effective crack bridging mechanism as result of increasing in micro fiber content as well as the generated synergy from different fiber types. Therefore, especially the coalescence of the cracks was inhibited and thus, the failure load ($P_{\max}$) increased. In other words, it can be said that the sum of the performance of the fibers in ternary fiber hybridization were highest in terms of synergy of different fiber types. In conclusion, according to the results obtained from this study, it can be addressed that the increase in bond strength of ternary fiber reinforced beam specimens exceeded $\sqrt[5]{f_c}$ with regard to beam specimens without fibers. However, quaternary hybrid fiber reinforced SCC beam specimens had the lowest bond strength with 5.1 MPa in all fiber reinforced SCC beam specimens. This result may be attributed to the reduction of OL 13/0.16 micro steel fiber replaced by OL 6/0.16 micro fiber with short length. Because, the shorter straight micro steel fibers can be expected to perform poorly in bridging the cracks. It can be emphasized from this result that straight short fibers should only be used in very high-strength concrete such as more than or equal 100 MPa.

4.4 Comparison between the experimental bond strength and predicted bond strength equations

In the study of Orangun et al. [28], it was reported that transverse reinforcement improves the bond performance. They developed a comprehensive expression to predict the bond strength of reinforcing bars with and without transverse reinforcement. In order to predict the average bond strength, the following equation was proposed for the bars not confined by transverse reinforcement:

$$u = \left(0.10 + 0.25\frac{c_{\min}}{d_b} + 4.15\frac{d_b}{l_d}\right) f_c'^{\,1/2} \quad (2)$$

where c_{min} is the minimum of the concrete cover or half of the clear spacing between the splices (mm), d_b is the bar diameter (mm), l_d is the splice length (mm) and f_c' is the compressive strength of concrete (MPa). A seen in Eq. 2, the bond strength evaluation is defined as the function of $f'_c{}^{1/2}$.

Zuo and Darwin [29] expanded the study of Darwin et al. [39] and they found that $f'_c{}^{1/4}$ represents more realistically the contribution of compressive strength of the concrete to bond strength. For bars not confined by transverse reinforcement, they derived an equation as follows:

$$u = \left(0.23 + 0.46\frac{c_{\min}}{d_b} + 14.05\frac{d_b}{l_d}\right)\left(0.1\frac{c_{\max}}{c_{\min}} + 0.9\right) f_c'^{\,1/4} \quad (3)$$

where c_{min} = min(c_x, c_y, c_s/2) and c_{max} = max (min (c_x, c_s/s), c_y) in which c_x is the spacing between the bars, c_y is the bottom cover and c_s is the clear spacing between the splices (mm), d_b is the bar diameter (mm), l_d is the splice length (mm) and f'_c is the compressive strength of concrete (MPa).

Esfahani and Rangan [30] introduced a new parameter, M, to consider the influence of the bond stress distribution over the bar in different splice lengths. The derived expression for the bond strength of bars not confined by transverse reinforcement was presented in Eq. 4.

$$u = u_c\left(\frac{1 + \frac{1}{M}}{0.85 + 0.024\sqrt{M}}\right)\left(0.88 + 0.12\frac{c_{med}}{c}\right) \quad (4)$$

where for $f'_c \le 50$ MPa (normal strength concrete)

$$u_c = 4.9\left(\frac{\frac{c}{db} + 0.5}{\frac{c}{db} + 3.6}\right) f_{ct} \quad (5)$$

for $f'_c > 50$ MPa (high strength concrete)

$$u_c = 8.6\left(\frac{\frac{c}{db} + 0.5}{\frac{c}{db} + 5.5}\right) f_{ct} \quad (6)$$

$$M = \cosh\left(0.0022L\sqrt{3\frac{f_c'}{d_b}}\right) \quad (7)$$

u_c is the local bond strength, c_{med} = med (c_x, c_y, (c_s + d_b)/2) and c = min (c_x, c_y, (c_s + d_b)/2) in mm, L is the splice length (mm), $f_{ct} = 0.55\sqrt{f_c'}$ (MPa).

According to ACI 318 [31], the splice length shall be as follows for deformed bars:

$$l_s = 1.3\ l_d;\ \frac{l_d}{d_b} = \frac{3}{40}\left(\frac{f_y}{\sqrt{f_c'}}\frac{'d_b}{c}\right) \quad (8)$$

where α, β, γ and λ' in Eq. 8 are safety factors and α is the reinforcement location factor, β is coating factor, γ is reinforcement size factor and λ' is lightweight aggregate concrete factor. Combining the Eq. 8 with $\pi d_b l_s = A_b f_y$ and setting the appropriate factor values (α, β, γ and λ' are 1 for all beams), the splice bond strength was obtained.

A comparison between the experimental test results of bond strength and the predicted bond strength values evaluated by using the equations proposed by Orangun et al. [28], Zuo and Darwin [29], Esfahani and Rangan [30] and ACI 318 [31] were presented in Table 6. The mean bond efficiency for all specimens were calculated as 0.76, 0.90, 0.80 and 1.61 with a standard deviation of 0.12, 0.15, 0.13 and 0.26 using the equations proposed by Orangun et al. [28], Zuo and Darwin [29], Esfahani and Rangan [30] and ACI 318 [31], respectively. The results showed that in this study, Eq. 3 which was proposed by Zuo and Darwin [29] provided better estimation and by using that equation, closer bond strength values were obtained with the experimental bond strength values. Especially, in the specimens reinforced with binary fiber hybridization of macro steel fiber and PVA fiber, the bond efficiency was calculated as 1.00 as can be seen in Table 6. Also, Esfahani and Rangan [30] equation gave good results especially in the specimen having ternary fiber hybridization by an average of 3% error. In Fig. 6, it was shown that all of the bond strength values were calculated as the same in both the equation of Zuo and Darwin [29] and Esfahani and Rangan [30]. However, the formula in ACI 318 [31] underestimated the bond strength values of fiber reinforced SCC specimens, for example, the measured bond strength of the beam specimens reinforced with ternary fiber hybridization was two times of the predicted results.

The results in this study were consistent with those of Diab et al. [40] who also found that the equations of

Table 6 Comparison between the measured and predicted bond strength

Mix Code	Measured bond strength, u_t (MPa)	Predicted bond strength (MPa)				Bond efficiency			
		Orangun et al	Zuo and Darwin	Esfahani and Rangan	ACI 318	$u_t/u_{Orangun}$	u_t/u_{Zuo}	$u_t/u_{Esfahani}$	u_t/u_{ACI}
SCC	4.11	7.19	6.18	6.85	3.41	0.57	0.67	0.60	1.21
MA1	5.73	7.64	6.36	7.28	3.62	0.75	0.90	0.79	1.58
MA1–P	6.22	7.25	6.20	6.91	3.44	0.86	1.00	0.90	1.81
MA0.8–13MI0.2	5.84	7.51	6.31	7.16	3.56	0.78	0.93	0.82	1.64
MA0.8–13MI0.2–P	6.77	7.32	6.23	6.98	3.47	0.92	1.09	0.97	1.95
MA0.8–13MI0.1–6MI0.1–P	5.11	7.24	6.20	6.90	3.43	0.71	0.82	0.74	1.49

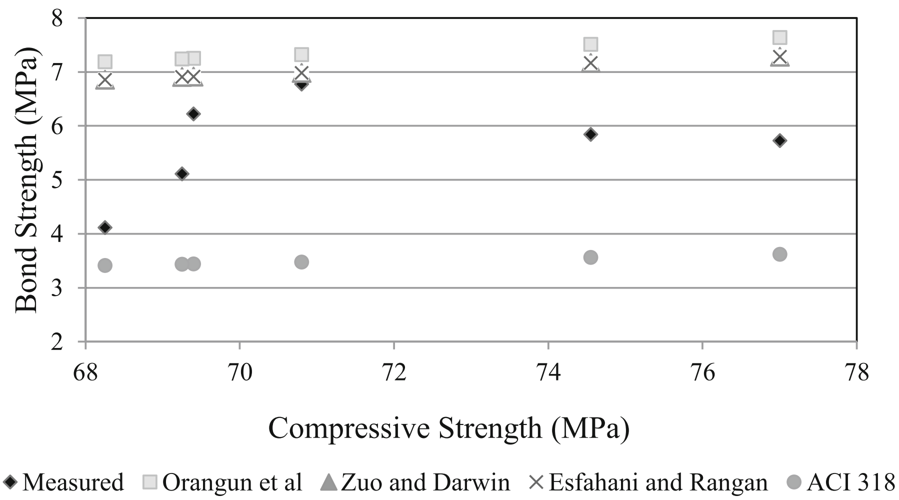


Fig. 6 Comparison of measured and predicted bond strength values

Zuo and Darwin [29] and Esfahani and Rangan [30] gave more accurate results compared to those obtained using Orangun et al. [28] and ACI equations. Moreover, in the study of Mohebi et al. [27] about the polypropylene fiber effect on the bond performance, it was concluded that the equation of Zuo and Darwin [29] achieved a better ratio between the measured and predicted bond strength values. In addition to these, when Hamad et al. [25] studied about the effect of hooked-end steel fiber reinforcement on bond strength, they also found in their research that ACI 318 [31] formula underestimated on the bond strength. Finally, based on comparison between the results of measured in experiments and predicted by the formulas of Zuo and Darwin [29] and Esfahani and Rangan [30], it could be addressed that $f'_c{}^{1/4}$ leads to a better estimation on the bond strength for fiber reinforced SCC beam specimens. However, it must be emphasized that in these empirical equations proposed by the researchers mentioned above, the presence of fibers and the effect of fiber hybridization were not reflected to the equations. As it was also mentioned in the study of Rossi et al. [41], the prediction equations of bond strength should include the parameters that reflect the presence of fiber. In this study, a new equation was proposed by using the experimental data that contained the fiber hybridization.

4.5 Proposed equations to calculate the bond strength in hybrid fiber reinforced self-compacting concrete

In this study, in order to reflect the effect of fiber hybridization on bond strength, the parameter of λ, which was FR-Index as defined in Table 5, was introduced and the following nonlinear formulation was derived for hybrid fiber reinforced self-compacting concrete beams;

$$\frac{u}{(f_c')^X} = c_1 + \exp\left[\left(\frac{\lambda + C_{\min}}{d_b}\right)^{c_2}\right] \lambda = V_f * \frac{L_f}{d_f} \qquad (9)$$

where c_{min} is the minimum of the concrete cover or half of the clear spacing between the splices (mm), d_b is the bar diameter (mm), V_f was the fiber content by volume and L_f/d_f was the aspect ratio of fibers. Also, c_1 and c_2 were the coefficients obtained from the regression analysis. In the literature, $f'_c{}^{1/2}$ and $f'_c{}^{1/4}$ was generally used to display the contribution of compressive strength on the bond strength values as given formulations in Sect. 4.4. Therefore, in the proposed equation obtained from 12 number of large scale fiber reinforced SCC beams, both ½ and ¼ subscript values of f'_c was taken into consideration and in Eq. 9, it was shown as variable x. As a result of nonlinear regression analysis, the following results belong to the proposed equation for $f'_c{}^{1/2}$ and $f'_c{}^{1/4}$ were obtained;

In order to prove that the findings were meaningful, according to T-distribution table and F-distribution table, t_{stat} and F_{stat} values should be higher than 1.812 and 4.96, respectively. As can be seen in Table 7, the obtained nonlinear empirical equations satisfied the t_{sat} and F_{stat} requirements. Hence, it is safe to state that the results of equations were meaningful. Besides, root mean square error (RMSE), which measures the difference between the estimated data and reference data in the model, was used with the aim of determining the most appropriate equation in the estimation of bond strength of fiber reinforced self-compacting concrete. Finally, the error analysis results showed that the use of $f'_c{}^{1/2}$ leads to a better estimation on bond strength of fiber reinforced self-compacting concrete due to having smaller error with 0.061 than that of $f'_c{}^{1/4}$ with 0.175. Therefore, in this study, the proposed nonlinear formulation in the calculation of bond strength of fiber reinforced self-compacting concrete was given in Eq. 10.

$$u = -4.75 f_c'^{\,1/2} + \exp\left[\left(\frac{\lambda + c_{\min}}{d_b}\right)^{0.82}\right] f_c'^{\,1/2} \qquad (10)$$

where λ is the multiplication of the volume and the aspect ratio of fiber $\left(\frac{V_f L_f}{d_f}\right)$ and the aspect ratio $\left(\frac{L_f}{d_f}\right)$ varies for each fiber type.

As can be seen in Fig. 7, there is a high correlation between the measured bond strength value and the bond strength estimated from the proposed equation except the one reinforced with quaternary fiber hybridization. It was obvious that the increase of λ caused generally an improvement on bond strength. However, the increase in the fiber type caused a reduction on the effectiveness of the equation proposed by this work. In the specimens having no fiber, the ones reinforced with single fiber and binary and ternary fiber hybridization, the change in bond strength value measured by test and obtained from proposed equation (Eq. 10) was in the range of 0.5%–9.7%. However, for the specimens with quaternary fiber hybridization, higher rate of change with 18.4% was calculated between the measured bond strength by test and calculated bond strength from the proposed equation due to the use of shorter micro steel fiber instead of longer one. It could be concluded that, fiber hybridization is a good way to improve the bond strength especially for the ternary usage and the proposed equation gave better estimation in the specimens reinforced with single fiber and binary and ternary fiber hybridization.

Bond efficiency values were calculated by dividing the measured bond strength values (from large scaled beam test) by the obtained bond strength values (from the empirical formulations). As can be seen in Fig. 8, bond efficiency values of Eq. 10 for each specimen were closer to 1 compared to the other ones obtained from other formulations in the literature. In fact, in the specimens having no fiber, single fiber, binary and ternary fiber hybridization, the bond strength values calculated were so close to the real measured values except for quaternary fiber hybridization with 0.84. It

Table 7 Nonlinear regression analysis results for proposed equations

	Coefficients		t_{stat}	F_{stat}	RMSE	R^2
x = 1/2	c_1	– 4.75	5.494	13.42	0.065	0.573
	c_2	0.82	5.544			
x = 1/4	c_1	– 6.48	3.425	11.55	0.196	0.536
	c_2	1.18	7.180			

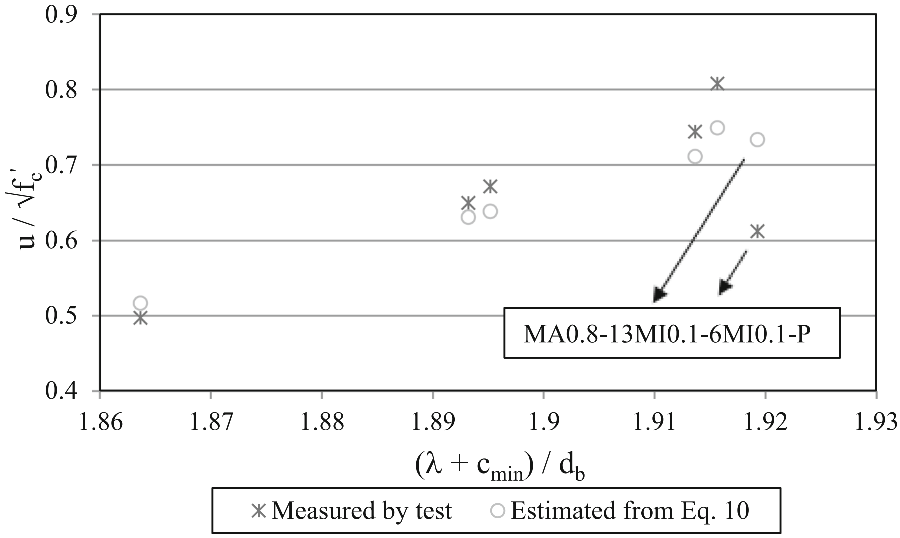


Fig. 7 The effect of fiber volume and aspect ratio on the bond strength

was revealed that the accuracy of the bond strength values calculated by using proposed equation (Eq. 10) depended on fiber hybridization. Because the prediction accuracy of bond strength obtained by proposed equation (Eq. 11) reduced as the diversity of fibers included into hybrid fiber reinforced mixture increased.

5 Conclusion

In this paper, the influence of hybrid fiber hybridization on the bond performance of SCC beam specimens have been experimentally investigated by using large-scale beams having tension lap-spliced reinforcing bars. Based on the test results, the following conclusions were drawn:

- The beam specimens having binary hybridization with PVA and ternary fiber hybridization exhibited further ductile behavior with higher amount of multiple micro-cracks. This would also provide opportunity the longer service life of reinforced concrete structures, especially at the infrastructure and industrial applications.
- The highest improvement for the load capacity of SCC beam specimens was obtained by use of the ternary fiber hybridization in SCC mixtures while the SCC beam specimens having quaternary fiber hybridization had lowest improvement with 26% compared to the specimens with no fiber.

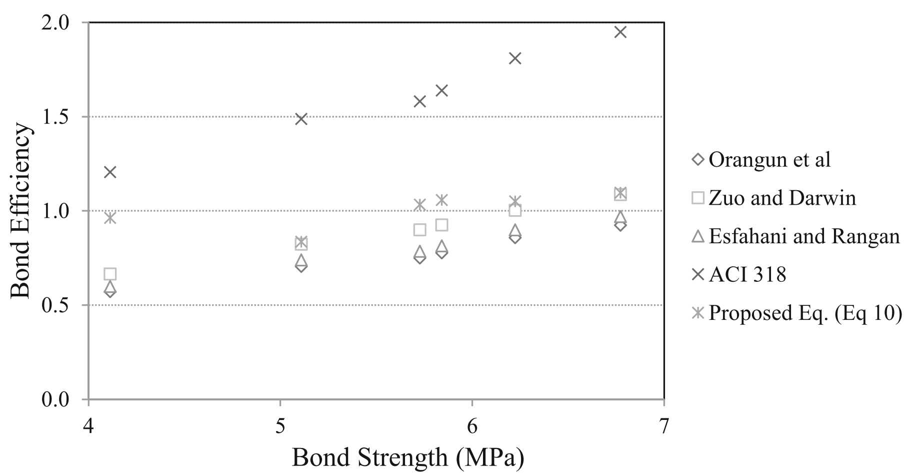


Fig. 8 Bond efficiency comparison between the proposed equation (Eq. 11) and the other empirical equations in the literature

Moreover, the improvement of residual load carrying capacity as result of the use of hybrid fibers would inhibit the development of plastic hinges at the column ends during earthquake.

- The bond strength of SCC beam specimens with ternary fiber hybridization indicated highest improvement with 65.9% followed by the specimens having binary fiber with PVA, binary fiber with 13/0.16 micro steel, single fiber and quaternary fiber as compared to SCC beam specimens with no fiber. Hence, it can be clearly emphasized from here that the use of PVA synthetic micro fiber at hybrid fiber reinforced SCC beams had positive effect in general on the bond strength between reinforcing bar and surrounding concrete as result of the achieved synergy with long and short steel fibers.
- Moreover, the improvement of the bond strength of ternary fiber reinforced beam specimens exceeded $\sqrt[5]{f_c}$ compared to beam specimens without fibers. Thus, it would be possible to reduce the stirrup spacing in beam-column joints.
- Results indicate that the equation of Zuo and Darwin provided the best estimation of bond strength. Besides, the equation of Esfahani and Rangan also gave good results especially in the specimen having ternary fiber hybridization by an average of 3% error. However, ACI 318 equation underestimated the bond strength of specimens about 60%.
- A prediction equation derived by nonlinear regression analysis estimated the bond strength values so close to the real measured values except for quaternary fiber hybridization. Namely, the bond efficiency values of the specimens having no fiber, single fiber and reinforced with binary fiber hybridization was calculated as 1.

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Availability of data and material All data and materials support the published claims and comply with field standards.

Code availability Software application or custom code support the published claims and comply with field standards.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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