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EFFECT OF HYBRID FIBERS ON BOND STRENGTH OF FIBER REINFORCED CONCRETE

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ABSTRACT

Essential additives, such as fibers, are widely used to improve the mechanical properties and performance of concrete. Fibers can be added to concrete in a mono or hybrid form of both metallic and non-metallic type. Although benefits of hybrid fibers addition to concrete are established in the literature, the bond stress slip response of embedded reinforcing steel in hybrid fiber reinforced concrete is not thoroughly studied. In this study, the bond stress-slip behavior of reinforcing steel bars embedded in concrete containing hooked end steel fibers and polypropylene fibers is assessed by carrying out pull-out tests. The variables considered in this study include polypropylene fiber volume (*i.e.* 0.1% and 0.2%), hooked end steel fiber volume (*i.e.* 0.5% and 1%), and the diameter of embedded reinforcement bars (*i.e.* 10 mm and 12 mm). The experimental results indicate that adding hybrid fibers of 0.1% polypropylene and 1% hooked end steel fibers yield the highest bond strength and hence the highest reduction in the embedded (development) length. The addition of hybrid fibers to concrete also improved the toughness of concrete and increased the slip measurements prior to failure of the bond between rebar and concrete.

Keywords: fiber reinforced concrete, pull-out test, steel fibers, polypropylene fibers, bond stress, embedment length.

1. INTRODUCTION

In recent years, large-scale projects are developed intensively in transportation, construction, and other fields where concrete is the main construction material in structural members. Consequently, continuous developments in the performance of concrete is ongoing in several aspects, including compressive, tensile, and bond strengths. One of the main drawbacks of concrete is its lower tensile strength compared to other construction materials such as steel and fiber-reinforced polymers. This led to various types of fibers being extensively tested as additives to concrete in the past few decades to improve its tensile strength and enhance other properties. Asbestos fibers, and natural fibers, such as flax, wood, palm, jute, bamboo, *etc.* are among the first types that were tested [1]-[5]. These natural products fibers have the advantage of low environmental impact and low manufacturing costs [6]. With the rapid development in the industry, synthetic fibers, *i.e.* metallic and non-metallic, are widely produced with various shapes and dimensions and added to concrete to improve its properties and performance [7]-[14].

The enhancements of mechanical properties of concrete is found to substantially influence the bond performance between concrete and rebar [12]. Degradation in rebar-concrete bond intact in reinforced concrete members may lead to a localized failure in the contact area around the rebar. This may occur due to the low capacity in the tension ring stresses in the concrete zone as a result of the pulling in reinforcement [14]. Thus, increase in tensile strength of concrete may lead to an improved bond response. Several research efforts have been made to improve the rebar-concrete bond response by addition of fibers. The majority of existing studies were devoted to the use of a single fiber type, mostly steel fibers. Roy *et al.* [13] studied the influence of steel fiber volume fraction and direction on the pull-out conduct of rebar embedded in ultra-high-performance steel reinforced concrete. The results show that bond stresses increase as volume fractions increase. Further, the study indicates that higher pull-out load is captured when fibers direction perpendicular to the load direction compared with fibers direction parallel to the load direction. Hamad *et al.* [8] studied the influence of steel fibers on bond strength of different size hooked bars in beam-column joint in normal-strength concrete for different fiber volume fraction percentage (0.5 %, 1% and 1.5%). The results indicate the significant and positive effect of steel-fiber in increasing bond strength. In addition, the study found that optimum fiber content for the mixture proportions used in the study to be 1.0%. Hamad and Abou Haidar [9] studied the influence of steel fibers on bond strength of different size hooked bars in beam-column joint in high-strength concrete for different fiber volume fraction percentage. The results indicated that addition of steel-fiber to concrete increase bond strength. Sturm and Visintin [15] studied the influence of adding two types of steel fiber (short & long), variation, and cover on bond strength of ultra-high-performance fiber reinforced concrete by using pull-out test for 69 samples. The results indicated there is no significant effect on bond strength based on changing the steel fiber type, however, cover thickness has a significant role in improving bond strength.

Other efforts are made to examine the bond performance of reinforcement bars embedded in hybrid fibers concrete. Ganesan *et al.* [11] studied the effect of hybrid fiber (*i.e.* steel and polypropylene fibers) on high-performance concrete by varying the volume fractions of the hybrid fibers, diameters and embedded length of rebars in concrete. The results showed the combination of a 1% volume fraction of steel fiber with 0.1% volume fraction

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of polypropylene fibers significantly improve the bond stress for 12mm, 16mm, and 20 mm diameter rebars by about 50%, 46% and 33%, respectively. Hameed *et al.* [10] investigated the effect of hybrid fiber (*i.e.* Amorphous metal and carbon steel hooked-end fibers) on normal strength concrete by using the fiber in mono form and hybrid form. Fibers were added to the concrete mixture as mono and hybrid forms where the dosages were 40 kg/m^3 and 20 kg/m^3 from each type (total of 40 kg/ m^3 of hybrid fibers), respectively. Also, hybrid fibers dosage was increased to 40 kg/m^3 from each (total of 80 kg/m^3 of hybrid fibers). The results indicate the bond stress of the concrete mixture that possesses 80 kg/m^3 of hybrid fiber (40 kg/m^3 from each type) showed significant improvement compared to concrete without any fibers. Moreover, Huang *et al.* [12] studied the effect of adding hybrid fiber (Crimple steel and polypropylene) on bond strength between rebar and hybrid-fiber reinforced concrete (HFRC) under monotonic and cyclic loading by varying fiber volume fraction and aspect ratio. For steel fibers, increase in volume fraction and aspect ratio improves bond strength while, for polypropylene fibers, increase in volume fraction enhances bond strength but increase in aspect ratio lead to decreased bond strength. Lin and Ostertag [14] investigated the pull-out resistance of rebar embedded in hybrid fiber (*i.e.* polyvinyl alcohol (PVA) and hooked-end steel fibers) reinforcing concrete with the addition of transverse spirals. The results showed hybrid fiber reinforced concrete (HFRC) with the addition of transverse spirals have more pull-out resistance compared with the control concrete specimens.

Based on these limited studies, bond strength of rebar embedded in hybrid-fiber reinforced concrete of hooked end round steel fiber and polypropylene fiber with hyper-plasticizers in the mix is not well established in literature. Thus, the objective of this paper is to evaluate the bond stress-slip response of hybrid fiber reinforced concrete by carrying out pull-out tests considering various variables. The examined parameters in this study include the mixture composition of hooked end round steel fibers and polypropylene fibers, and the diameter of the steel rebar. The bond stress-slip response is evaluated through carrying out pull-out tests which is a common approach that was developed to quantify the bond of the reinforcement bars when embedded in a concrete mixture.

2. EXPERIMENTAL PROGRAM

The experimental program consisted of testing 42 specimens for assessing the effect of adding hybrid fibers to reinforced concrete on the rebar embedment length and bond strength. The varied parameters in the study are the volume fraction of steel fibers (V_s), the volume fraction of the propylene fibers (V_p), the diameter of the embedded rebars (d_b), and the embedment length (l_d). The examined parameters were compared to control specimens that contained no fibers as well as no hyper-plasticizers.

2.1 Utilized Materials

The concrete materials used in casting the specimens consisted of Ordinary Portland cement (Type I), natural clean sand as fine aggregates, crushed stone as coarse aggregates, and water. In addition, a polymer with long lateral chains as hyper-plasticizer was added to improve workability for concrete mixtures contained hybrid fibers as discussed in the next sections. Sieve analyses of the coarse and fine aggregates were conducted as per ASTM C136 [16] to determine their particle size distribution. Table-1 and Table-2 show the sieve analyses results of coarse and fine aggregates, respectively. The results indicate that the used aggregates in the concrete mix patch conform to the limits of ASTM C33 [17]. The embedded reinforcing bars in the concrete specimens are of two sizes: 10 and 12 mm grade 420 deformed bars.

Table-1. Sieve analysis result for used coarse aggregates.

No.	Sieve No. (mm)	Retained (g)	Passing %	ASTM C33 Limits
1	(9.5)	0	100	100 %
2	#4 (4.75)	30	98	90-100%
3	#8 (2.36)	242	83.6	75-100%
4	#16 (1.18)	560	61.9	55-90%
5	#30 (0.6)	910	38.1	35-59%
6	#50 (0.3)	1331	9.4	8-30%
7	#100 (0.15)	1426	2.9	0-10%

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Table-2. Sieve analysis result for used fine aggregates.

No.	Sieve No. (mm)	Retained (g)	Passing %	ASTM C33 Limits
1	12.5	0	100	100 %
2	9.5	304	85.4	85-100%
3	#4 (4.75)	1855	10.7	10-30%
4	#8 (2.36)	2061	0.77	0-10 %
5	#16 (1.18)	2065	0.58	0-5%

Two type of fibers were added to concrete in either a single or a hybrid form to improve the mechanical properties of the concrete. These fiber types are: (a) hooked end round steel fibers, and (b) polypropylene fibers. The shape and type of these fibers are shown in Figure-1. The dimensions and the tensile strength of the used fibers are listed in Table-3.

Table-3. Properties of steel and polypropylene fibers.

Type of fiber	Length (mm)	Diameter (mm)	Ultimate tensile strength (MPa)
Steel	35	0.55	1345
Polypropylene	18	0.015	350

Figure-1. Used fibers: (a) hooked end round steel fibers and (b) polypropylene fibers.

2.2 Mixture Preparation

All tested specimens were casted from concrete mixtures that contained a similar proportion of the following basic materials: 350 kg/m^3 of cement, 750 kg/m^3 of sand, 1090 kg/m^3 of coarse aggregate, and 175 kg/m^3 of water. Five concrete mixtures were considered in this study based on the type and the quantity of the additives as follow: a control mixture labeled as "C" that does not contain any additives, two mixtures with different volume fractions of polypropylene fibers labeled as "P1" and "P2", and two mixtures with different volume fractions of polypropylene and steel fibers labeled as "H1" and "H2". For mixtures H1 and H2, a hyper-plasticizer was added to the mix to improve the workability of the mix. The details of the concrete material mixture proportions are presented in Table-4.

Table-4. Concrete mixture types and their proportions.

Mixture type	Cement (kg/m^3)	Sand (kg/m^3)	Aggregate (kg/m^3)	Water (kg/m^3)	V_s (%)	V_p (%)	Hyper-plasticizer (L/m^3)
C	350	750	1090	175	0	0	0
P1	350	750	1090	175	0	0.1	0
P2	350	750	1090	175	0	0.2	0
H1	350	750	1090	175	0.5	0.1	1.5
H2	350	750	1090	175	1	0.1	1.5

The selected quantities of cement, sand, and aggregate, shown in Table-4, were mixed inside a drum mixer initially for a time duration of 2 minutes. During the mixing process, steel fibers and half amount of the water quantity were added. This was followed by adding the hyper-plasticizer as well as the rest of the water quantity and polypropylene fiber portion to the mixture and mixing for about 3 minutes resulting in a total mixing time of 5 minutes.

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2.3 Specimens Fabrication

The reinforced concrete specimens were casted in standard cylindrical molds of 150 mm diameter and 300 mm height. A reinforcing steel bar was partially embedded along the longitudinal axis of each cylinder. The bars had extensions outside the concrete cylinders of 320 to 400 mm to allow gripping of the bars by the testing machine. The specimens were then left to cure in a controlled curing tank before testing as shown in Figure-2.

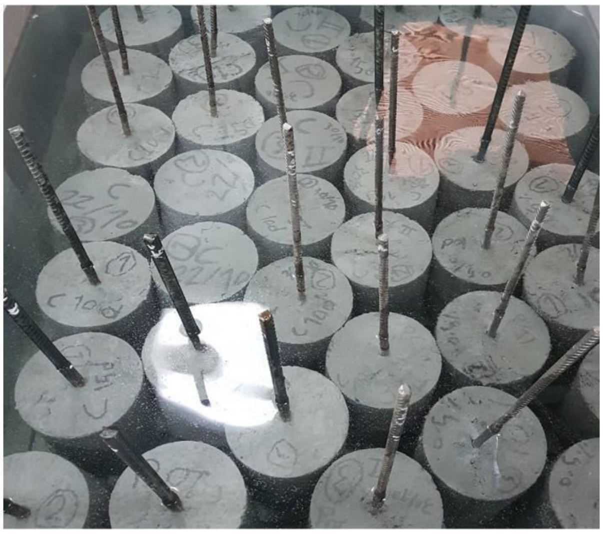

Figure-2. Curing process for pull-out and compressive strength tests.

A set of 14 cases were considered based on the five mixture types (Table-4), the reinforcing bar diameters (d_b) of 10 and 12 mm, and the embedment length (l_d) taken as 10 and 15 times the diameter of the bars (10 d_b and 15 d_b). The details of the considered 14 cases and their parameters are presented in Table-5. For each examined case, three specimens were fabricated, tested, and then the average value was considered.

Table-5. Details of the considered 14 cases and their parameters.

Case No.	Case label	V_s (%)	V_p (%)	Plasticizer (L/m^3)	Rebar diameter d_b (mm)	Embedded length type l_d
1	C1.1	0	0	0	10	10 d_b
2	C1.2	0	0	0	12	10 d_b
3	C1.3	0	0	0	10	15 d_b
4	C1.4	0	0	0	12	15 d_b
5	P1	0	0.1	0	10	10 d_b
6	P2	0	0.2	0	10	10 d_b
7	H1.1	0.5	0.1	1.5	10	10 d_b
8	H1.2	0.5	0.1	1.5	12	10 d_b
9	H1.3	0.5	0.1	1.5	10	15 d_b
10	H1.4	0.5	0.1	1.5	12	15 d_b
11	H2.1	1	0.1	1.5	10	10 d_b
12	H2.2	1	0.1	1.5	12	10 d_b
13	H2.3	1	0.1	1.5	10	15 d_b
14	H2.4	1	0.1	1.5	12	d_b

2.4 Test Setup and Procedure

A universal testing machine with 100 kN capacity was used to conduct pull-out tests and evaluate the bond-slip behavior of the 42 specimens. During testing, the cylindrical specimen was enclosed by a custom-made rigid loading base that was securely fixed to the bottom platen of the testing machine as shown in Figure-3. The loading base was used for fixing the specimen to the bottom platen

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and only applying the load on the rebar. The pull-out test was performed by monotonically applying a tensile load at the extended side (top) of the reinforcing bar away from the specimen at a slow loading rate that ensures a quasi-static behavior. The load was continued until the failure of the specimen by either yielding of the reinforcing steel bar (*i.e.* when the resulting tensile stress is higher than the rebar yield strength) or by excessive slip of the steel bar (*i.e.* when the resulting tensile stress is lower than the rebar yield strength). The test setup is shown in Figure-3. The pull-out load and total displacement (*i.e.* slip measurements and axial deformations of the rebar) of the bar were recorded automatically by the testing machine. The presented slip values were calculated by subtracting the rebars axial elastic and plastic deformations from the total displacement recorded by the testing machine. Nonetheless, the axial deformation within the elastic range of the rebars were found to be small compared to the values of the slip.

Compressive strength tests were also conducted on standard cylindrical specimens (150 mm by 300 mm) that were casted from the same patches of the five mixture types (Table-4).

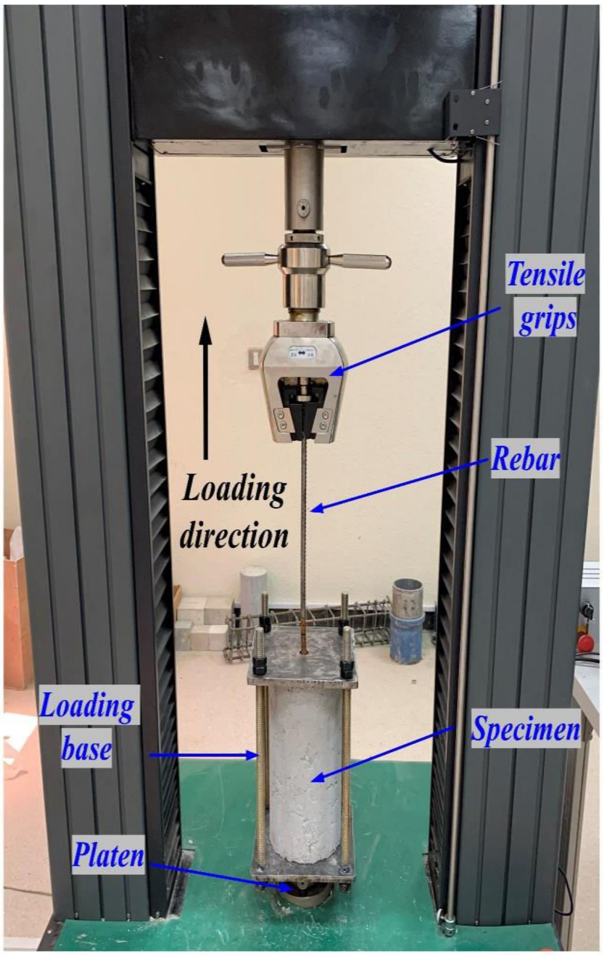

Figure-3. Pull-out test setup on cylindrical concrete specimen with embedded rebar.

3. RESULTS AND DISCUSSIONS

The pull-out test results were analyzed in two steps: (1) cases with propylene fibers only, and (2) cases with hybrid fibers. Table-5 presents the details of the considered cases and their parameters. The results of the pull-out and compressive strength tests are listed in Table-6. The 28 days compressive strength values of the specimens varied from 20 to 35 MPa as presented in Table-6. The yield and ultimate tensile strengths of the used reinforcing bars are about 575 MPa and 669 MPa, respectively [18].

Specimens with propylene fibers of 0.1% and 0.2% (*i.e.* P1 and P2) were examined initially to obtain the proper proportion that can be used for the hyper fiber-reinforced concrete specimens. The selected proportion was based on their ultimate pull-out load and compressive strength. The results in Table-6 show that the specimen with less propylene fibers P1 (V_p = 0.1%) reach to a higher compressive strength than specimen P2 (V_p = 0.2%). Moreover, the ultimate pull-out load for case P1 is higher than case P2 due to lower portion of propylene fiber (Table-5). Thus, a volume fraction of 0.1% propylene fibers was utilized as a reference for fabricating the specimens with hybrid fibers in this study.

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Table-6. Pull-out and compressive strength tests results.

Case No.	Case label	Compressive strength (MPa)	Slip at ultimate stress, mm	Ultimate load, kN	Ultimate bond stress, MPa	Failure mode
1	C1.1	20.53 (28 days)	3.03	7.87	2.51	pull-out
2	C1.2		6.62	27.34	6.04	pull-out
3	C1.3		3.29	15.8	3.35	pull-out
4	C1.4		9.17	58.8	8.66	pull-out
5	P1	17.3 (7 days)	2.90*	14.47	4.6	pull-out
6	P2	10.4 (7 days)	2.21*	9.17	2.91	pull-out
7	H1.1	34.69 (28 days)	3.47	10.77	3.43	pull-out
8	H1.2		8.16	37.72	8.34	pull-out
9	H1.3		4.17	20.21	4.29	pull-out
10	H1.4		11.70	71.54	10.54	pull-out
11	H2.1	30.93 (28 days)	3.09	13.18	4.2	pull-out
12	H2.2		8.00	52.03	11.5	pullout
13	H2.3		5.87	26.09	5.54	pull-out
14	H2.4		28.54	91.13	13. 43	yielding

*Values were not corrected for the axial deformations of the rebars

3.1 Specimen Behavior

The bond stress-slip responses were constructed to examine the behavior of specimens and compare it to the control specimens as shown in Figure-4. The average bond stress (τ_b) was calculated based on the applied pull-out load (P) and the contact surface of the embedded part of the reinforcing bar as given in equation (1).

$$\tau_b = P / (\pi\, d_b\, l_d) \qquad (1)$$

In general, the specimens exhibited a nonlinear bond stress-slip response with a maximum point that is followed by a reduction in bond stress as shown in Figure-4. It can be observed that for cases with d_b = 10 mm, the nonlinear behavior is more pronounced when compared to cases with d_b = 12 mm that showed some linear response segments.

In all the specimens (except H2.4) a pull-out failure mode was observed. This pull-out failure mode causes concrete spalling around the rebar as shown in Figure-5. The shape of bond stress-slip curve of such a failure is characterized by smooth softening after reaching the ultimate bond stress. This is because the response is dominated by the interaction between concrete and the reinforcing bar. On the other hand, yielding failure mode occurred when the bond strength is significantly large and hence the pull-out load causes yielding of the reinforcing bar before significant slip occurs. This was the case for specimen H2.4, which had V_s = 1.0% and 180 mm embedded length. The response of the specimen H2.4 showed that even when the reinforcing bar reached strain hardening, the bond resistance was maintained and stable. This shows an improved performance compared to the control specimens and also to specimens with V_s = 0.5% where not only higher bond stress values were reached but also lower slip at any given stress level.

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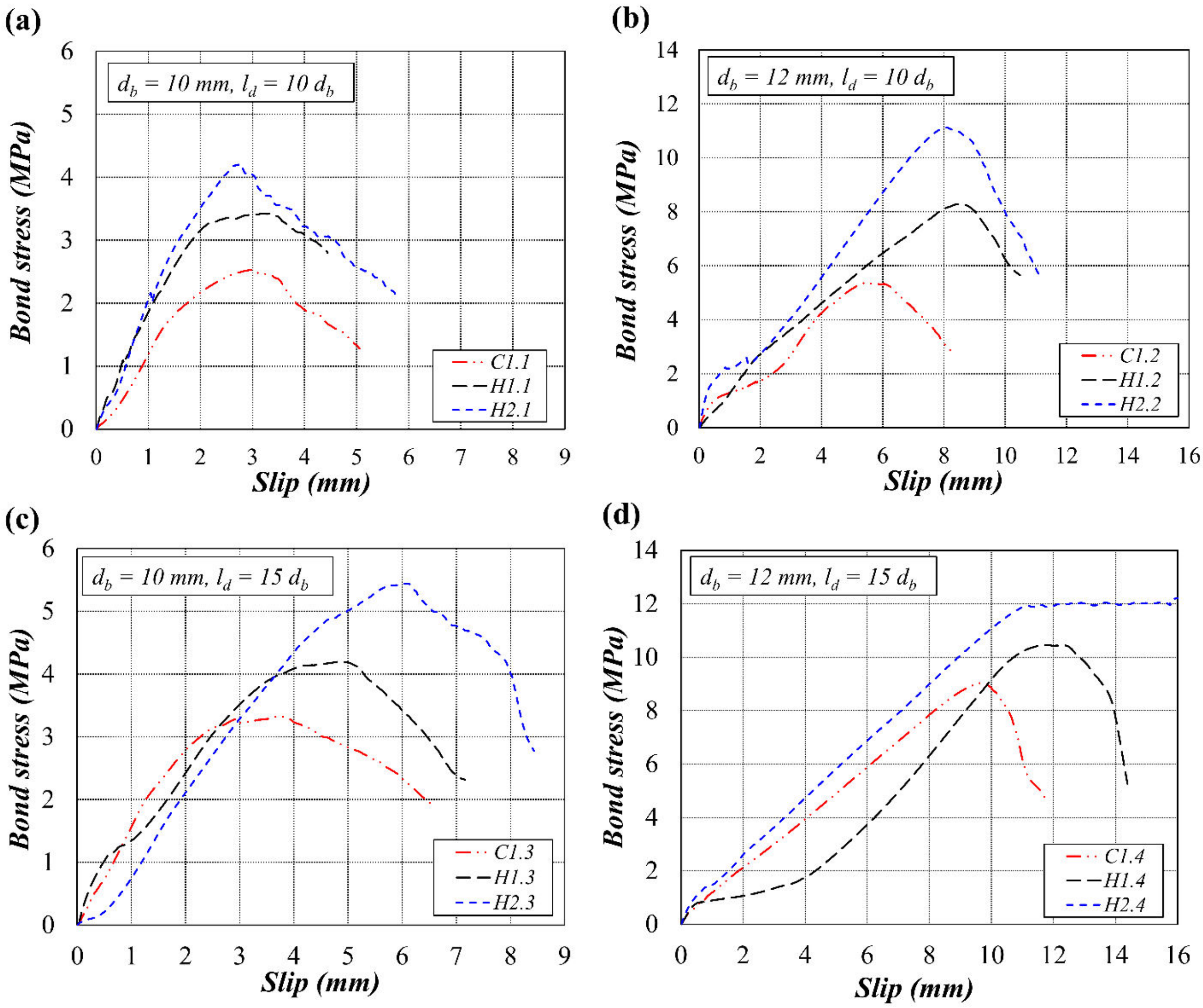

Figure-4. Bond stress-slip responses for control and hybrid specimens: (a) $d_b = 10$ mm and $l_d = 10\ d_b$, (b) $d_b = 12$ mm and $l_d = 10\ d_b$, (c) $d_b = 10$ mm and $l_d = 15\ d_b$, and (a) $d_b = 12$ mm and $l_d = 15\ d_b$.

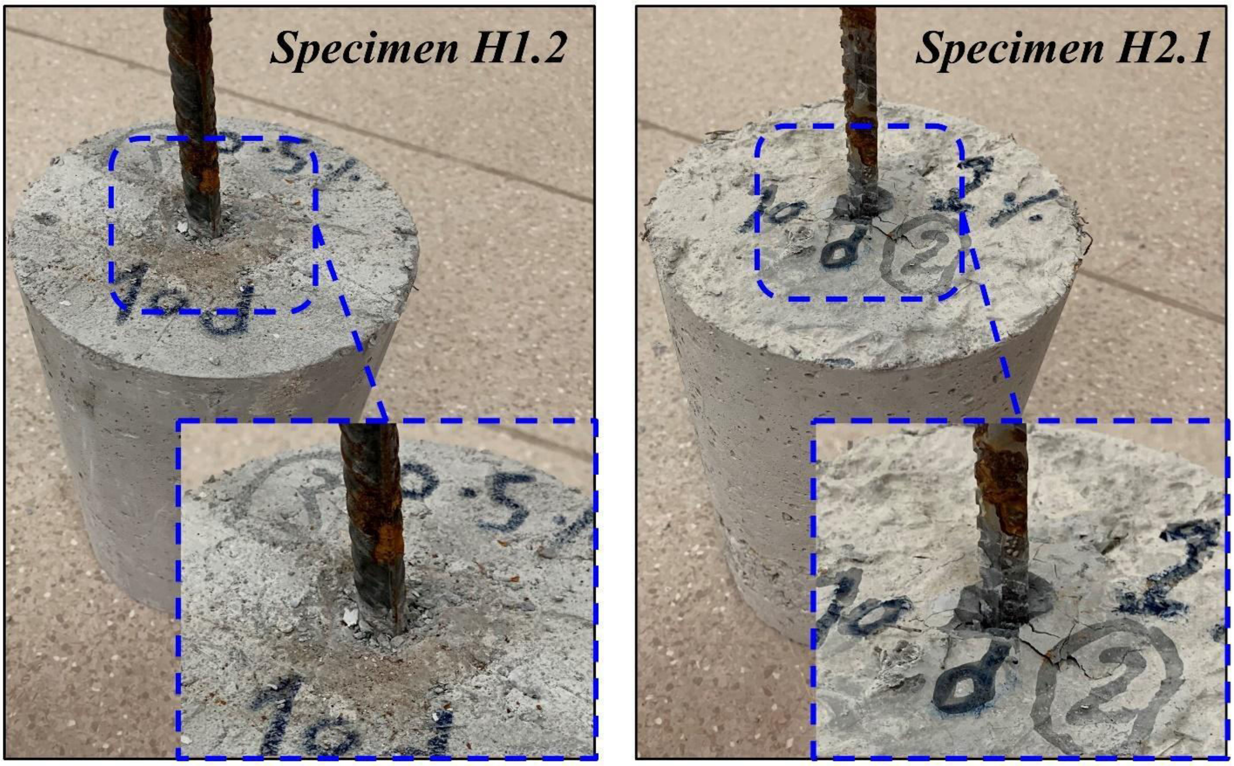

Figure-5. Specimens after testing with pull-out failure mode.

3.2 Bond Strength

The bond strength was determined by taking the average of the maximum stress values from the three tested specimens for each case as presented in Table-6. The responses for each case were plotted and grouped based on the diameter and the embedded length of rebar as shown in Figure-4 to compare the specimens with hybrid fibers to the control specimens.

Generally, it can be observed that cases with larger bar diameters (d_b) and hence higher embedded lengths have higher ultimate load and bond strengths than their counterparts with smaller d_b. It also can be noticed that for all cases adding hybrid fibers results in an increase in the bond strength compared to the control cases. More specifically, using higher volume fraction of steel fibers leads to higher values of the bond strength. This increase ranges from 21 to 37% for cases with V_s = 0.5%, and from 55 to 90% for cases with V_s = 1.0% as shown in Figure-6. This indicates the significant contribution of the added hybrid fibers to maintain the tensile cracks in concrete due to the pull-out loading and hence increased the bond strength. The figure also suggests that the increase in the bond strength for cases with larger embedded length (15 d_b) is lower than cases with smaller embedded length (10 d_b). This observation is more pronounced for specimens with V_s = 0.5%. It should be mentioned that although hybrid fibers specimens with V_s = 1.0% resulted in a higher bond strength, their compressive strength is lower than those with V_s = 0.5%.

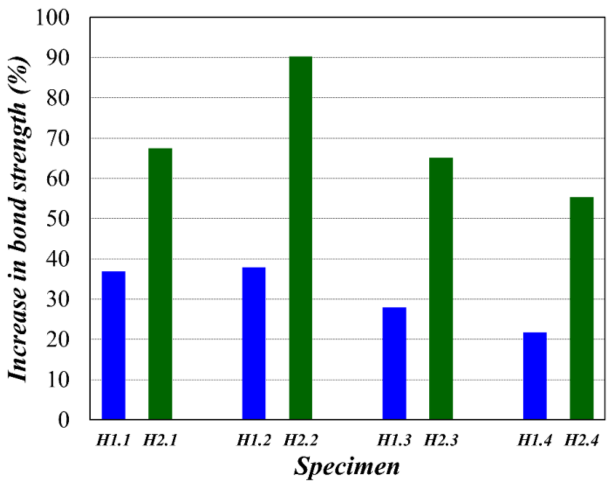

Figure-6. Increase in bond strength for the hybrid fibers cases compared to the control cases.

The slip values of the specimens for cases with hybrid fibers are fairly equal or lower than those of the control cases at any given stress level, which indicates an enhanced bond resistance. Nonetheless, this effect is less pronounced when compared to the effect on the bond strength. For all cases except the ones with d_b =10 mm and l_d = 10 d_b, the slip at ultimate bond stress of specimens with hybrid fibers was higher than those of the control specimens.

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3.3 Embedment Length

As discussed earlier, the addition of hybrid fibers leads to an increase in the bond stress of the specimens. Consequently, a specimen with shorter embedded length can reach the same bond stress level as a specimen with larger embedded length by adding fibers to the specimen. To show this, the tested specimens were grouped based on their bar diameters, and the bond strength against the embedded length for each case was plotted as shown in Figure-7. As can be seen, the bond stress level of the control cases at the 15 d_b level can be reached by the hybrid cases at shorter embedded lengths. For example, the bond stress corresponding to the control specimen with d_b of 10 mm at l_d of 15 d_b can be reached by l_d of 12.6 d_b and 11.0 d_b by cases with hybrid fibers of V_s of 0.5% (H1) and 1.0% (H2), respectively.

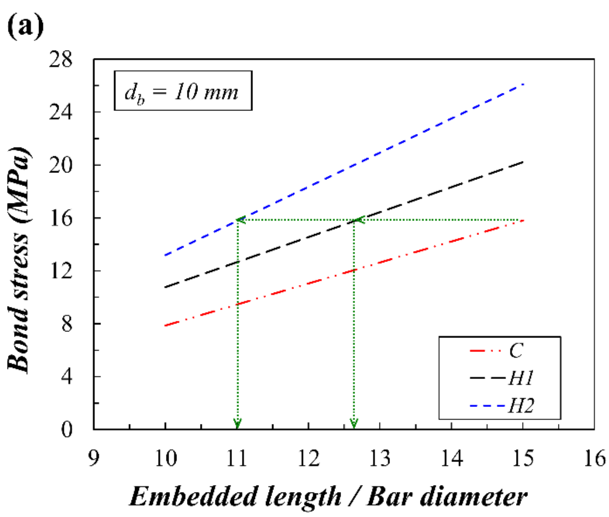

Figure-7. Bond strength-embedded length/bar diameter for cases: (a) d_b = 10 mm, and (b) d_b = 12 mm.

The reduction in the embedded length ranged from about 12% to 27%. Similar to the increase in the bond stress, the reduction in the embedded length for cases with V_s of 1.0% is higher than those of V_s of 0.5%. It can be also noted that the reduction in the embedded length does not seem to be dependent on the bar diameter as shown in Figure-8.

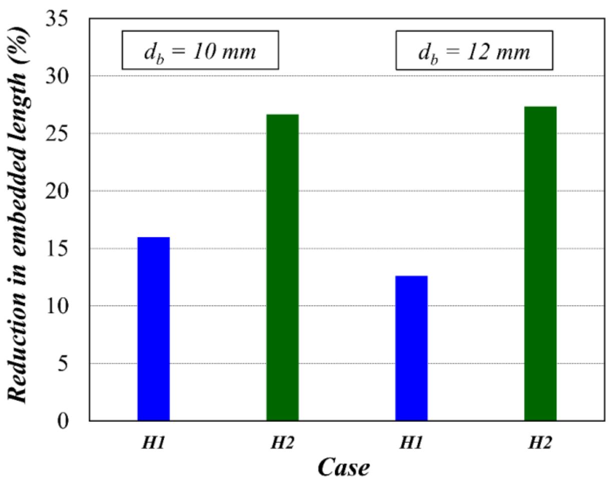

Figure-8. Reduction in rebar embedded length for the hybrid fibers cases compared to the control cases at $l_d = 15\ d_b$.

3.4 Toughness

Toughness is an important indicator of the performance of the specimens under pull-out loading. Higher toughness values indicate increased bond strength and deformability. Thus, it is of interest to evaluate the toughness values for the tested specimens. Toughness can be simply obtained by numerically integrating the area under the bond stress-slip curve. For the specimens tested in this study, the toughness values are presented in Table-7. The increase in toughness ranges from 29 to 66% for cases with V_s = 0.5%, and from 77 to more than 300% for cases with V_s = 1.0% as shown in Figure-9. The figure also suggests that the increase in toughness is related to the embedded length for cases with V_s = 1.0%. Thus, incorporating the selected hybrid fibers in concrete mixture improve concrete toughness and provide concrete types that can be suitable for certain structural applications as in structures subjected to extreme loading (earthquake, blast, fire *etc.*).

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Table-7. Toughness values of the tested specimens.

Case No.	Case label	Toughness (MPa-mm)
1	C1.1	9.32
2	C1.2	32.86
3	C1.3	15.53
4	C1.4	53.18
7	H1.1	12.86
8	H1.2	54.82
9	H1.3	20.1
10	H1.4	74.8
11	H2.1	16.52
12	H2.2	74.12
13	H2.3	30.79
14	H2.4	300.44

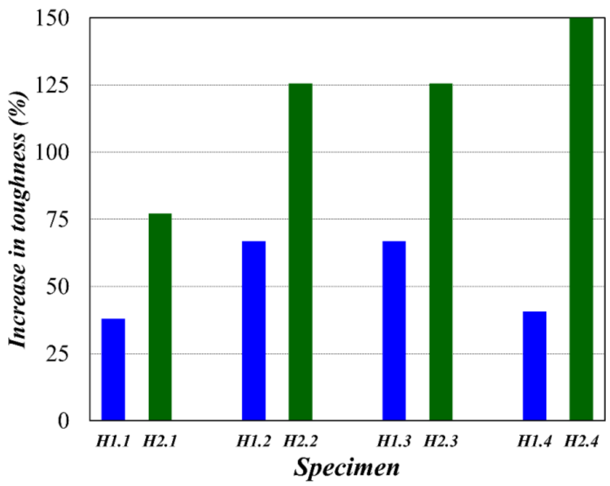

Figure-9. Increase in toughness for the hybrid fibers cases compared to the control cases.

4. CONCLUSIONS

The bond stress-slip behavior of hybrid fiber reinforced concrete with embedded reinforcing bars was experimentally investigated by conducting pull-out tests on concrete specimens containing hybrid fibers of hooked-end steel and polypropylene. The considered parameters are the fibers volume fractions, the diameter of the reinforcing bar, and the embedment length. Based on the analysis of experimental regime results, the following conclusions can be drawn:

a) Concrete specimens with hooked-end steel and polypropylene hybrid fibers showed a significant improvement in the bond stress-slip response compared to conventional concrete specimens with no fibers.

b) A reduction of 12% to 27% in the required embedment (development) length for reinforcing bars can be adopted when hooked-end steel and polypropylene hybrid fibers are added to concrete in similar volume fractions as in this study (V_s = 0.5 to 1.0%, V_p = 0.1 to 0.2%).

c) Specimens with higher steel fiber volume fraction (V_s = 1.0%) reached a higher increase in ultimate bond stress than specimens with lower steel fiber volumes fraction (V_s = 0.5%).

d) The addition of steel and polypropylene fibers into reinforced concrete significantly enhanced its toughness compared to conventional reinforced concrete specimens. The improved toughness of hybrid fiber reinforced concrete makes it preferable for certain structural applications such as earthquake and blast resistant structures.

5. Notation

The following symbols are used in this paper:

V_p : volume fraction of polypropylene fiber
V_s : volume fraction of steel fiber
d_b : diameter of rebar
l_d : embedded length
P : pull-out load
τ_b: average bond stress

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