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Evaluation of Bond Strength of Reinforcement in Concrete Containing Fibers, Micro-silica and Nano-silica

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Abstract

The present study analyzes the bond stress in steel reinforcements embedded in concrete containing polymer fibers, micro- and nano-silica particles. For this purpose, 36 cylindrical (with a diameter of 10cm and height of 15cm) and 36 cubic (10 × 10 × 10cm) specimens containing different contents of additives and three types of cement strength grade (i.e. 32.5, 42.5 and 52.5MPa) were constructed and subjected to pull-out and compressive strength tests, respectively. The experimental observations were then compared to previously proposed models available in the literature. The results indicated that micro- and nano-silica particles, compared to fibers, had more impacts on improving the reinforcement-concrete bond strength. Moreover, the highest bond strength was observed for the specimen containing equal content of micro- and nano-silica particles. An acceptable agreement was also obtained between the results of current study and previous models, highlighting the capability of the proposed models in prediction of the actual behavior of such specimens.

Nomenclature

F_y	Yield strength of rebar	W_m	Unit weight of rebar
d_b	Diameter or equivalent diameter of rebar	E_r	Effective modulus of elasticity of rebar
η	Global efficiency factor of rebar	W	Water
C	Cement	HRWR	High range water reducer
$\tau_{\max}$	Reinforcement-concrete bond strength	S	Local slip of rebar
c	Thickness of concrete coverage	l_d	Length of reinforcement embedded in concrete
f'_c	Compressive strength of concrete	η_2	Coefficient of continuity
ϕ	Diameter of rebar	$k_m k_{tr}$	Coefficient of lateral rebars

1. Introduction

The bond strength between reinforcing rebar and mortar in a reinforced concrete is one of the major factors affecting the mechanical behavior of this composite material [1, 2]. It is reported that there are three types of forces available on the reinforcement-concrete interface as friction force, molecular bond strengths, and mechanical thread strength [3].

Numerous parameters affect the bond of concrete and reinforcement, including the concrete strength, yield strength of the steel, diameter and surface geometry of the reinforcement, the position of the reinforcement in the concrete, the embedded depth of reinforcement in the concrete (coupling), the depth of concrete cover surrounding the reinforcement, the use of spiral reinforcement, and the types of aggregates and admixtures used [4, 5]. Pull-out test can be mentioned as the

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oldest, simplest, most common and most practical approach for evaluating the reinforcement–concrete bond and investigating the bond stress–slip evolution [6]. To date, different studies have been conducted to evaluate the effects of various parameters on reinforcement–concrete bond strength. In this regard, Darwin et al. indicated that the impact of concrete strength on bond strength of unconfined and confined reinforcements by secondary steel making is consistent with (fc')1.4 [7]. The effects of aggregates were investigated in another study, where the results highlighted the significant impact of amount of coarse aggregate on bond force arising from secondary steel making [8]. Furthermore, Ferguson et al. showed that beams with more inferior coverage exhibited more bond strength [9]. The pull-out tests conducted by Ferguson et al. emphasized that splitting occurs in concrete specimens with less coverage compared to specimens with more coverage [10]. In a very thick coverage, the shear cracks are generated in distance between tracks. So the shear bond crack (pull-out crack) occurs instead of splitting [11]. Diameter fittings may affect the amount of bond stress. The pull-out tests conducted by Viwathanatepa et al. showed that bond strength intensifies after increasing the diameter of reinforcement [12]. Soroushian et al. reported that increased reinforcement diameter in confined concrete reduces the bond strength; It was also stated that the reduction of bond strength has linear relation with reinforcement diameter [13]. Zhou et al. showed that bond strength of reinforcements confined by secondary steel making increases at higher relative levels of groove and reinforcement diameter. It was shown that damage growth at reinforcement-concrete contact surface depends on concrete strength and fitting pattern of reinforcement [14].

As mentioned, various admixtures that are usually utilized in production of reinforced concrete can have effects on the reinforcement-concrete bond strength. Silica fume known as micro-silica is a byproduct used as pozzolan [15, 16]. The micro-silica was initially used to substitute parts of cement with this waste material to reduce the cost of used cement. With the rising cost of silica in many countries, this aforesaid application is not economical and so micro-silica is added to concrete as a multiplied material to reach the intended properties [17]. Micro-silica particles are a hundred times smaller than grains of cement and possess high level of response as their most significant property. More than 95 percent of micro-silica particles are smaller than 1 micrometer. The micro-silica contains high levels of non-crystalized silicon dioxide and large amounts of fine spherical particles. A small amount of iron, magnesium, and alkaline oxide can also be found [18]. Nili et al. reported the highest level of compressive strength of concrete at the ages of 7 and 28 days as the results of mixture containing 6% micro-silica and 7% nano-silica [19]. The use of nano-silica in concrete would also lead to increase in short and long term strength [20]. Resistance to water penetration, compressive strength, and some other characteristics of concrete will be improved by using these additives [21-23]. Moreover, polymer fiber (Polypropylene) is another suitable additive utilized as secondary reinforcement of concrete to reduce shrinkage, control cracking, and increase the long-term durability of concrete.

Regarding the whole studies conducted on the evaluation of reinforcement-concrete bond strength in different types of concrete, there is still a gap in our knowledge about the effect of polymer fibers and the combined effect of micro- and nano-silica on the reinforcement- concrete bond strength. Therefore, the present study applies experimental examinations in order to examine the reinforcement-concrete bond strength in specimens containing polymer fiber and micro- and nano-silica particles. Specifically, 36 cylindrical and 36 cubic specimens using 12 different mix designs and three different cement strength grades were constructed and exposed to pull-out and compressive tests, respectively. Then, the obtained results were evaluated and analyzed by the models provided by former researchers.

2. Experimental Plan

2.1. Materials and Mix Designs

In this study, three types of ordinary Portland cement (CEM I 32.5, 42.5, and 52.5MPa) procured from Bojnourd cement factory were utilized in construction of specimens. The fine and coarse aggregates with maximum nominal sizes of 4.75mm and 37.5mm, respectively, were provided from Sabzevar mines. The sieve analysis for the fine and coarse aggregates was performed according to the particle size distribution curve on the basis of ASTM regulations and the curves are depicted in Fig. 1.

Micro-silica, nano-silica, and polymer fibers provided by Vand Chemie Construction Company were added to the mix designs to improve their characteristics. Micro-silica can make the concrete anti-sulfate, leading to an increase in durability and strength and severe reduction permeability of concrete. Nano-silica is another applicable additive, which as a nano-based material and super-pozzolan liquid can be effectively utilized in cementitious products. Moreover, polymer fibers are appropriate for increasing tensile, bending, and pull-out strength of reinforced concrete structures [24, 25]. The physical properties of the used additives are listed in Table 1. The poly-carboxylate ether (PCE) based super-plasticizer was also used in mixtures based on the intended workability and slump value. Moreover, rebars with a diameter of 16 mm were used to prepare specimens for pull-out test. Table 2 presents the specifications of the used rebar. A total of 36 mix designs (12 mix designs for each cement strength grade) were used for preparation of the concrete specimens (Table 3). As seen, the mix design 1 was control experiment, which is without fiber, micro- and nano-silica additives. The mix designs of 2 to 6 were made with fiber and a water/cement ratio of 0.5, while the mix designs of 7 to 12 were prepared using micro- and nano-silica particles and water-cement ratio of 0.4. The total amount of micro- and nano-silica particles was considered at 10% of the consumed cement.

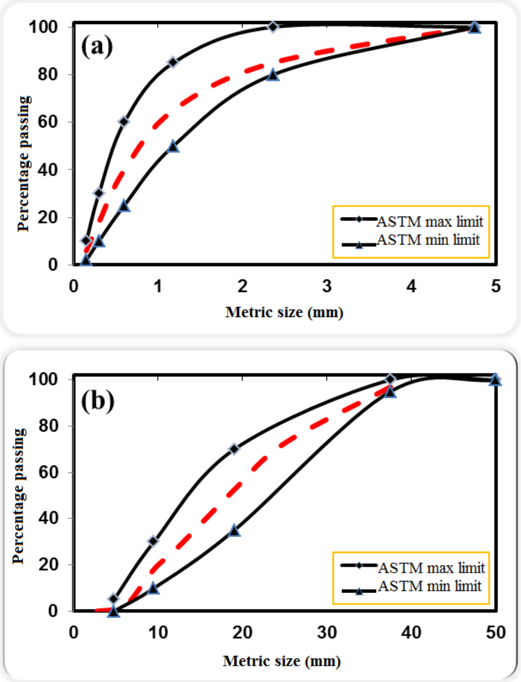

Fig. 1. Sieve analysis of (a) Fine and (b) Coarse aggregate.

Table 1
Physical properties of the used polymer fiber, micro- and nano-silica.

Property	Fiber	Micro-silica	Nano-silica
Color	White	White	No colour
Specific surface area (m^2/gr)	-	20-25	200-240
Density(gr/cm^3)	0.9	1.9	1.203-1.215
Particle size (nm)	20000	229	-
Particle shape	String	Globular	-
Viscosity	-	-	5.0
PH (at 20°C)	-	-	9.6-10.2
Structure	Solid	Amorphous	Liquid
Bulk density (kg/m^3)	-	300-500	-
Melting point (°C)	160	1230	-

2.2. Specimen Preparation and Testing

The preparation, construction, and curing procedures of the specimens are demonstrated in Fig. 2. As seen, rebars with a diameter of 16mm were used in construction of cylindrical specimens. For placement of reinforcements exactly in the middle of the cylindrical specimens and implementation of the experiments with higher accuracy, the wooden parts with a hole as big as the reinforcement diameter in its middle were used so that concrete casting was done from the side pores of woods. Finally, a total of 36 cylindrical (with a diameter of 10cm and a height of 15cm) and 36 cubic (10 × 10 × 10cm) specimens were constructed. In order to make the specimens distinct from each other, the rebars at specimens made with 32.5, 42.5 and 52.5MPa cement strength grades were, respectively, colored in white, red and green. The precise length of reinforcement placement inside concrete (embedded length) was already marked with different colors so that the results provide adequate accuracy. Moreover, curing of specimens was performed in water tank with a proper temperature and humidity condition.

Table 2
Specifications of the rebar used in the cylindrical specimens.

Property	Value
F_y= Yield strength	414 (N/mm^2)
W_m= Unit weight	0.617 (kg/m)
d_b = Diameter or equivalent diameter	16 (mm)
E_r= Effective modulus of elasticity	200×103 (N/mm^2)
η= Global efficiency factor	1

Fig. 2. Representation of the construction and curing process of the cylindrical specimens.

Table 3
A series of mix design used for construction of specimens using each cement strength grade (i.e. 32.5, 42.5 and 52.5MPa).

No.	C (kg/m^3)	W/C	Aggregate (kg/m^3)	Micro-silica (kg/m^3)	Nano-silica (kg/m^3)	Fiber (kg/m^3)	HRWR (kg/m^3)
1	555	0.5	1503	0	0	0	8
2	555	0.5	1503	0	0	3	8
3	555	0.5	1503	0	0	5	8
4	555	0.5	1503	0	0	8	8
5	555	0.5	1503	0	0	10	8
6	555	0.5	1503	0	0	13	8
7	500	0.4	1503	56	0	0	8
8	500	0.4	1503	40	16	0	8
9	500	0.4	1503	16	40	0	8
10	500	0.4	1503	28	28	0	8
11	500	0.4	1503	48	8	0	8
12	500	0.4	1503	0	56	0	8

Cement = C, Water = W, High range water reducer = HRWR

The cylindrical and cubic specimens were subjected to pull-out and compressive strength tests, respectively, at the concrete laboratory of Hakim Sabzevari University. The pull-out test was implemented by mean of Z with traction testing machine at the speed of 1 mm per minute (Fig. 3). The crack patterns of a series of specimens are shown in Fig. 4.

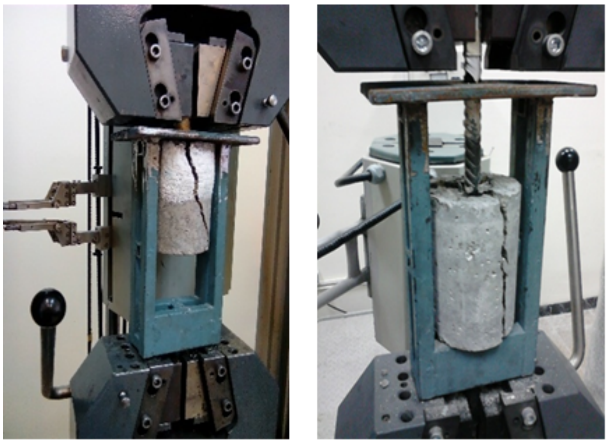

Fig. 3. The experiment setup of pull-out test.

3. Experimental Models in the Bond-slip Field

The local bond-slip relations in every spot of rebar length is a function of local slip of rebar (S) which, according to experimental results, is obtained under different geometric conditions and different strength of concretes. The experimental studies on bond and slip stress conducted by different researchers are demonstrated in Table 4. In these expressions, c is thickness of concrete coverage, d_b is diameter of steel reinforcement, ld is length of reinforcement embedded in concrete and is the characteristic compressive strength of concrete. η_2 is the coefficient of continuity conditions, which is equal to 1 for good condition and 0.7 for other conditions, is the diameter of the rebar, and are minimum and maximum thickness of concrete coverage, respectively, and is coefficient of lateral rebars.

Fig. 4. Representation of the crack patterns of specimens after pull-out test.

4. Results and Discussion

The experimental results obtained for all 36 specimens were compared and evaluated with the results of the previously presented models. Since compressive strength of concrete of previous models is amongst the affective factors in calculations. The results of compressive strength of all 36 specimens were demonstrated in Table 5.

Fig. 5 shows the relationship between maximum bond stress versus compressive strength of specimens. It can be observed that the values of bond stress and compressive strength of mixtures containing micro and nano-silica are in the ranges of 5.9 to 10.5MPa and 20 to 48MPa, respectively. The corresponding values for the mixtures containing polymer fiber are in the ranges of 4.2 to 8.5MPa and 20 to 44MPa, respectively. Accordingly, it can be stated that the mixtures

Table 4
Representation of reinforcement-concrete bond strength equations available in literature.

<table>
<tr><th>Unit</th><th>Stress conjunction equations</th><th>Reference</th></tr>
<tr><td>Psi</td><td>$\tau_{\max} = \left[1.22 + 3.23 + \frac{c}{d_b} + 53\frac{d_b}{l_d}\right]\sqrt{f'_c}$</td><td>Orangun et al. [26]</td></tr>
<tr><td>SI</td><td>$\tau_{\max} = \left[0.55 + 0.24\frac{c}{d_b}\right]\sqrt{f'_c} + 0.191\frac{A_t \cdot f_{yt}}{s \cdot d_b}$</td><td>Kemp & Wilhelm [27]</td></tr>
<tr><td>Psi</td><td>$\tau_{\max} = 232.2 + 2.716\frac{c}{d_b}\sqrt{f'_c}$</td><td>Kemp [28]</td></tr>
<tr><td>Psi</td><td>$\tau_{\max} = \left[3.5 + 3.4\frac{c}{d_b} + 57\frac{d_b}{l_d}\right]\sqrt{f'_c}$</td><td>Chapman & Shah [29]</td></tr>
<tr><td>SI</td><td>$\tau_{\max}\left[1.2 + 3\frac{c}{d_b} + 50\frac{d_b}{l_d}\right]\sqrt{f'_c}$</td><td>Pillai et al. [30]</td></tr>
<tr><td>Psi</td><td>$\tau_{\max} = \left[0.1 + 0.25\frac{c}{d_b} + 4.2\frac{d_b}{l_d} + 0.024\frac{A_{tr} \cdot f_{yt}}{s \cdot d_b}\right]\sqrt{f'_c}$</td><td>Harajli [31]</td></tr>
<tr><td>SI</td><td>$\tau_{\max} = A\left(\frac{c}{d_b}\right)^{B} \times (f'_c)^{\alpha}$
$\alpha = \begin{pmatrix} 0.58 & \text{Deformed} \\ 0.21 & \text{Plain} \\ 0.45 & \text{GFRP} \end{pmatrix}$
<table>
<tr><th></th><th colspan="3">Light weight concrete</th><th>Ordinary concrete</th></tr>
<tr><th>Constant</th><th>Deformed</th><th>GFRP</th><th>Plain</th><th>Deformed</th></tr>
<tr><td>A</td><td>0.85</td><td>0.46</td><td>0.3</td><td>0.74</td></tr>
<tr><td>B</td><td>0.17</td><td>0.68</td><td>0.88</td><td>0.52</td></tr>
</table></td><td>Bae [32]</td></tr>
<tr><td>SI</td><td>$\tau_{\max,\text{split}} = \eta_{26.5}\left(\frac{f_{cm}}{25}\right)^{0.25}\left(\frac{25}{\phi}\right)^{0.2} \times \left[\left(\frac{c_{\min}}{\phi}\right)^{0.33}\left(\frac{c_{\max}}{c_{\min}}\right)^{0.1} + k_m k_{tr}\right]$</td><td>CEB-FIP [33]</td></tr>
</table>

containing micro and nano-silica typically have more compressive strength and reinforcement-concrete bond stress compared to fiber-contained mix designs. The reason can be explained by the better performance of combined micro- and nano-silica compared to polymer fiber in improving the concrete properties. This is in agreement with the results of previous studies, where the higher bond strength is related to the higher compressive strength of concrete specimens [3, 34, 35].

Table 5
The results of compressive strength test conducted on 36 cubic specimens.

Mix No.	Compressive strength (MPa)		
	C 32.5	C 42.5	C 52.5
1	30	34	24
2	32	36	38
3	28	32	40
4	20	44	24
5	22	30	38
6	26	26	28
7	31	40	38
8	48	48	45
9	36	30	27
10	45	34	24
11	47	38	36
12	33	30	20

Fig. 6 represents the maximum bond strength for specimens made by the first six mix designs with three types of cement strength grade. Amongst the entire mix designs, models presented by Kemp [28] and Chapman and Shah [29], respectively, has the maximum and minimum values of bond strength as though it exhibits significant difference with experimental results. However, other models predict almost similar results which are close to the outputs obtained from the experiments of the current study.

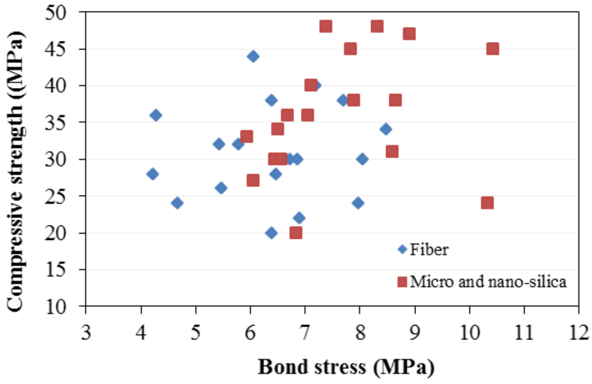

Fig. 5. Compressive strength versus bond stress of the tested specimens.

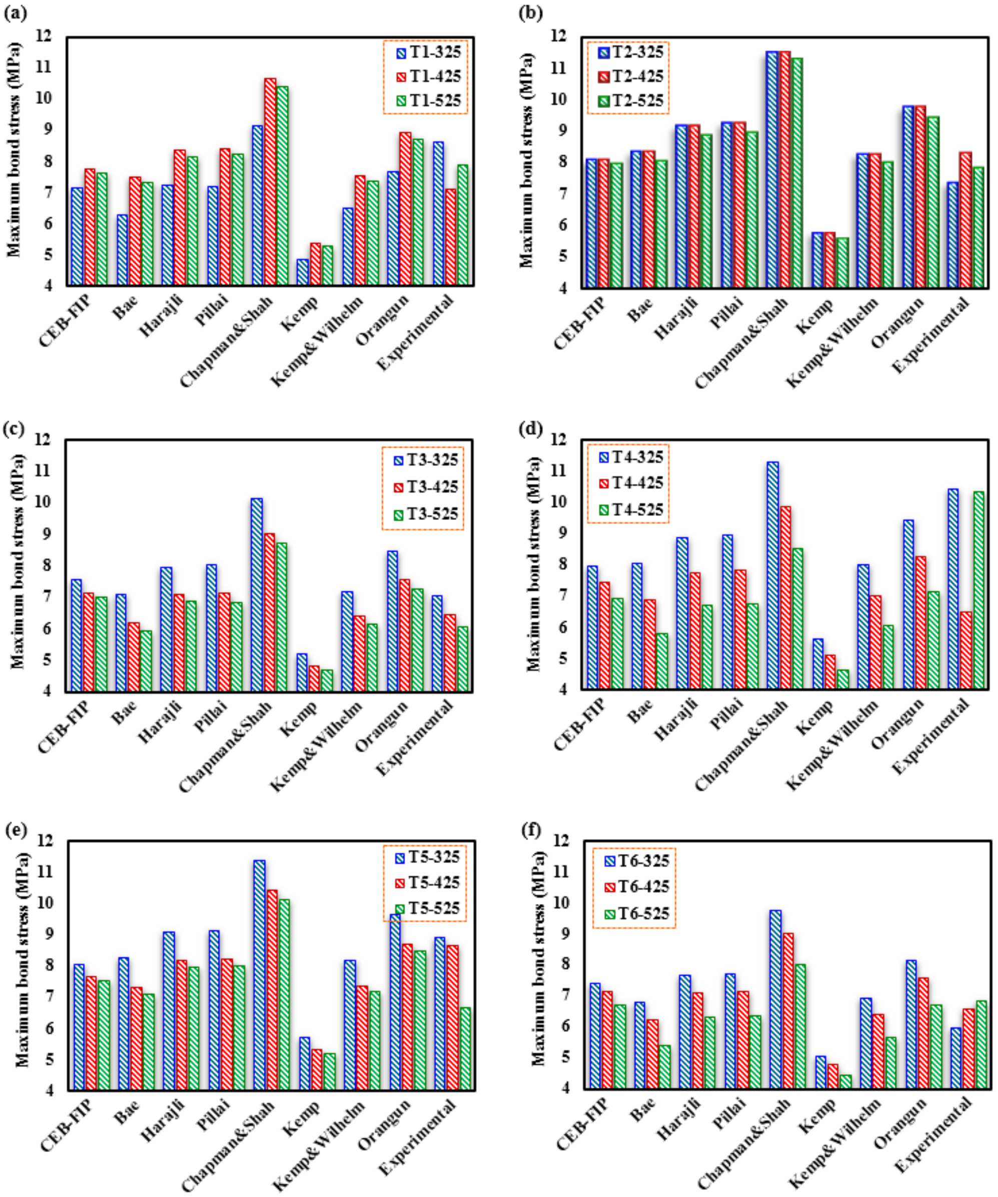

Fig. 6. Representation of the crack patterns of specimens after pull-out test.

Each part of the Fig. 6a-6f corresponds to a different mix design (1-6) and represents the results of three specimens constructed with different cement strength grades of 32.5, 42.5 and 52.5MPa. Moreover, it can be observed in Fig. 6c-6f that all the models predicts highest values for cement strength grade of 32.5MPa, while increasing the cement strength grade leads to a decrease in predicted bond strength. Therefore, it can be concluded that compressive strength of cement (cement strength grade) has no significant effect on reinforcement- concrete bond strength, while nowadays, the impact of cement strength grade is amongst the important issues for various concrete properties [16, 35-38]. Although the amount of fibers gradually increases from mix design 2 to 6, the maximum bond strength in experimental results (10.44MPa) is obtained for the specimen constructed by mix design 4 containing 8kg/m^3 fibers and cement strength grade of 32.5MPa. In other mix designs, there is no specific procedure so that the values obtained for bond strength in some mix designs are less than the values of control mix design. Thus, it can be mentioned that the use of polymer fibers does not provide noticeable improvement in reinforcement-concrete bond strength.

Fig. 7 demonstrates the bond strength evaluations for the second six mix designs (7-12) and the specimens containing different amounts of micro- and nano-silica particles. The results show that in these mix designs, similar to 6 fiber-contained mix designs, the models proposed by Kemp [28] and Chapman and Shah [29], respectively, exhibit the maximum and minimum values of bond strength. The other models present almost acceptable values for bond strength prediction. It can be also observed that in Fig. 7b, c, and e increasing the grade of cement strength leads to increase in predicted bond strength. However, this procedure is not true for experimental results of the current study. The maximum and minimum values of bond strength arising from experimental studies were, respectively, 7.97, and 4.22MPa for Fig. 7d (mix design 10 in Table 3) and Fig. 7f (mix design 12 in Table 3), which were both obtained from specimens made with cement strength grade of 52.5MPa. It should be noticed that the amounts of micro and nano-silica at mix design 10 are identical and equal to 28kg/m^3. Therefore, it can be concluded that similar content of these additives is an optimal value to achieve the maximum bond strength.

The comparison of bond strength provided between three types of cement strength grade used in this study shows that the average efficiency of fibers in 32.5, 42.5, and 52.5MPa are 6.46, 6.38, and 6.35MPa, respectively. However, these values for the specimens containing micro- and nano-silica additives are 8.06, 7.27, and 7.61MPa, indicating the better performance of these silica-based additives compared to polymer fibers. This confirms the results of previous researches, which showed that using these materials has been effective in improving the mechanical properties of concrete such as compressive, flexural, and tensile strength [39-41]. Since the previous models were typically presented for normal concretes, and there are few studies implemented on the effect of concrete additives and other materials on reinforcement-concrete bond strength, the results of the present study would facilitate the presentation of new models for more precise future researches.

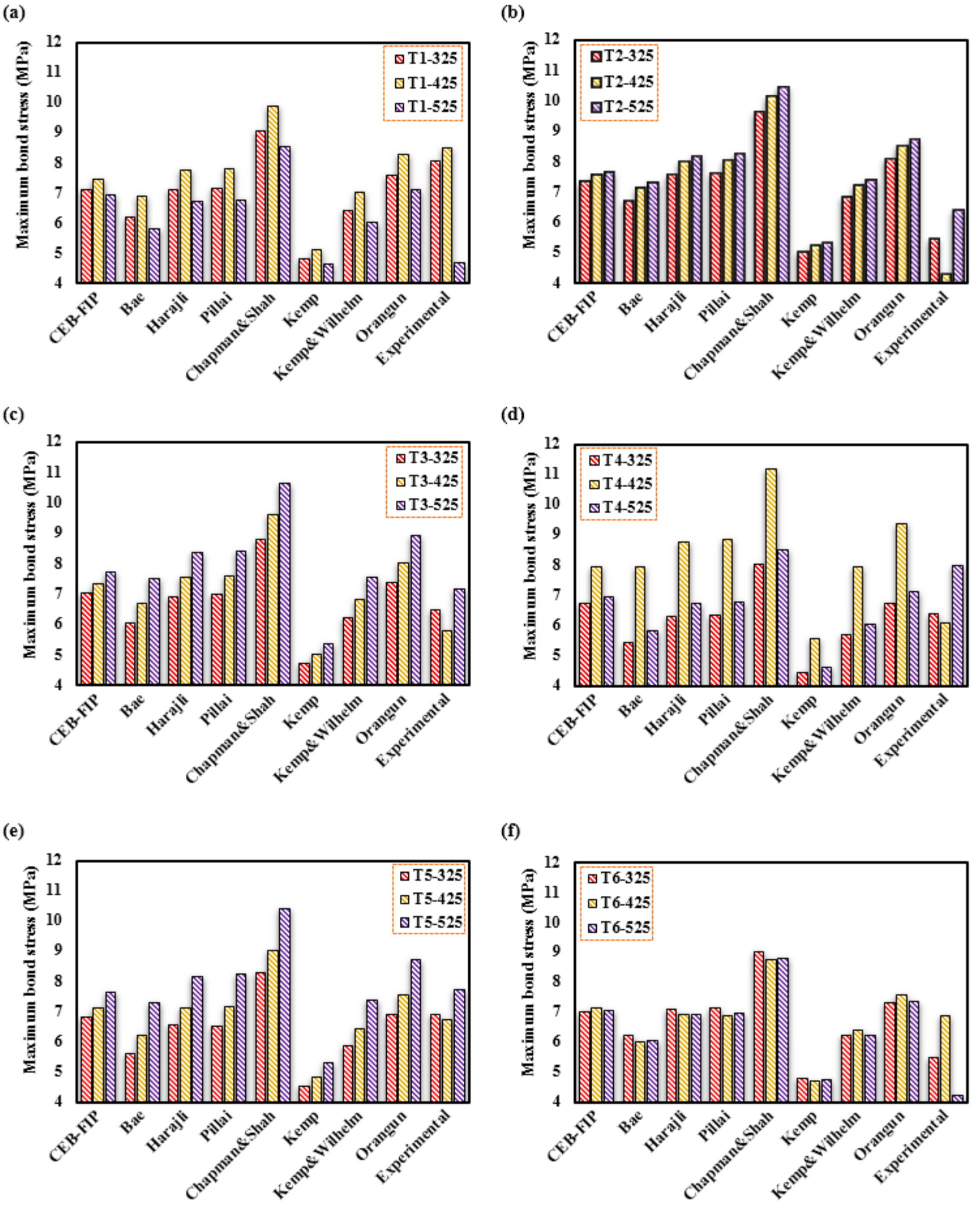

Fig. 7. Representation of the crack patterns of specimens after pull-out test.

5. Conclusions

The present study examined the effect of different contents of polymer fibers, and micro- and nano-silica additives on reinforcement-concrete bond strength. In this regard, 12 mix designs, each with three types of cement strength grade (i.e. 32.5, 42.5, and 52.5MPa), were utilized to construct 36 cylindrical and 36 cubic specimens, which were exposed to pull-out and compressive strength tests, respectively. The results were then evaluated and verified by previous models. The conclusion of this study can be summarized as follows:

1. Mix designs containing micro- and nano-silica typically had more compressive and reinforcement-concrete bond strength compared to fiber-contained mix designs.
2. Utilization of equal contents of micro- and nano-silica was obtained to be the optimal condition to result in the highest compressive and reinforcement-concrete bond strengths.
3. Increasing cement strength grade had more significant effects on improving the reinforcement-concrete bond strength of specimens containing micro- and nano-silica compared to the specimens containing polymer fibers.
4. Comparison of experimental results with the results of previous models indicated the acceptable agreement of the actual and predicted values.

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