STUDY OF BOND STRENGTH BETWEEN FIBER-REINFORCED-MORTAR/STEEL AND THEIR MECHANICAL PROPERTIES USING PUSH-OUT, TWIST-OFF AND PULL-OFF METHODS

ALI SABERI VARZANEH * , MAHMOOD NADERI
Department of Civil Engineering, Imam Khomeini International University, Qazvin, Iran

Today, it is significantly important to perform non-destructive tests to evaluate the quality of cement materials. However, in such tests, some parameters are typically measured indirectly to estimate the strength of the material by specific relations. Thus, the present study evaluates the compressive and flexural strengths of cement mortars reinforced with polypropylene fibers at different ages by using the slight-destruction twist-off and pull-off tests. For this purpose, using the linear and power regression analyses, the relationships between the results of the mentioned in-situ tests and the strengths of fiber-reinforced mortars were identified. Then, calibration diagrams were provided to translate the twist-off and pull-off results into the compressive and flexural strengths of the fiber-reinforced mortars. Also, given that the proper connection between cement materials and steel is one of the crucial issues in civil engineering, in this paper, has investigated the effect of polypropylene fibers on the shear and tensile bond strength between cement mortar and steel plates, using "Push-out", "Twist-off" and "pull-off" tests. At the end, using the finite element method (FEM), the fiber-reinforced and non-fiber reinforced samples were modeled, analyzing the effects of fibers on the tests. The results indicated a high correlation coefficient between the experimental results and semi-destructive tests. Moreover, the addition of fibers improved the behavior of cement mortars subjected to compression. The modeling results of the in-situ tests revealed the delayed cracks and increased strengths of the fiber-reinforced mortars. Also, the obtained results revealed the marked effect of fibers in increasing the bond strength between the mortar and steel.

Keywords: *Semi-destructive tests, Finite element method, Bond, Mortar, Steel*

1. Introduction

Fibers are employed to reinforce cement mortars since such mortars are brittle and offer low tensile strengths. Fiber-reinforced mortars not only are more ductile but also provide improved mechanical properties. However, the use of fibers was common in the past. For example, straw used to be added to mortar to prevent cracking. Polypropylene fibers have been commonly used in recent years. The advantages of fibers include influencing stress-strain curves [1] and improving the compressive behaviors of mortars and concrete under stresses [2, 3]. In addition, fibers affect cracks within mortars. The addition of polypropylene fibers to mortars prevents the growth and opening of cracks within the mortars [4]. The investigation of fiber effects on the tensile strengths of mortars indicated that the addition of fibers improved the compressive strength by 7.21% [5]. However, different fiber contents may yield different results. For example, the excessive fiber content of a cement material produces adverse impacts [6-8]. It was revealed that the addition of polypropylene fibers improved the compressive and tensile behaviors of mortars; however, the fiber content of above 0.3% negatively affected the mortar properties [9]. Thus, the present study adopts a fiber content of 0.3%.

In every hybrid structure built with a combination of concrete and steel rebar, rehabilitation could be required based on a variety of reasons. In some parts of the structure, covered concrete laid on reinforced members such as beams, columns, floors, and so on may be crashed in which rebar becomes exposed; this could lead to rusting and corrosion of reinforcement and damage the concrete section. These parts need remediation that lots of time could be achieved by fulfillment using cement mortars. The amount of adhesion between the concrete and the steel rebar is so crucial in terms of both structural behavior and cracks due to shrinkage. Several factors affect the adhesive strength including shrinkage of concrete covered the steel, geometry, and section of the rebar. The existence of some slight rusting on the surface of the steel bars results in mechanical adhesion [10]. Typically, the adhesive strength between surfaces is divided into three categories including adhesion, friction, and mechanical interference [11]. The adhesion is relevant to chemical connections. Friction happens when movements occur between surfaces; and mechanical interference is related to surface roughness. Berthet et al. investigated the bond strength between concrete and steel using push-out tests. They used different layers of adhesive between the concrete and steel. The bond strengths of concrete and steel with and without adhesive were obtained about 0.8 and 3.4 MPa, respectively [12].

* Autor corespondent/*Corresponding author*,
E-mail: Ali.saberi@edu.ikiu.ac.ir

It is required to employ in-situ tests to evaluate the mechanical properties of mortars. In-situ tests are classified into three groups, including non-destructive, semi-destructive, and destructive. Considering that experimental methods cannot provide a proper evaluation of the strength improvement of mortars at different ages, it is important to adopt in-situ tests. Destructive tests include the core-drilling [13] and pull-out [14] tests. However, destructive tests encounter limitations, such as high cost, considerable structural damage, and limited repeatability. Also, it was found that the real compressive strength of a structure was larger than the strength obtained in the core-drilling test [15]. Non-destructive tests include the ultrasonic method [16] Schmidt hammer method [17]. Non-destructive tests cannot be relied on since they evaluate the strength of materials indirectly. Semi-destructive tests include the pull-off [18], twist-off [19], and friction-transfer [20] methods. In the friction-transfer test, a core with a diameter of 50 mm is drilled on the mortar. Then, the friction-transfer machine is stabilized on the core, applying a torsional moment so the core would fail.

The present study employs the in-situ methods of twist-off and pull-off to examine the mechanical properties of polypropylene fiber-reinforced mortars. The mentioned methods were also used, along with the push-out test, to measure the shear and tensile bond strength between fiber-reinforced mortar and steel. Two typical cement mortars were used to carry out the tests. Then, a 0.3% content of polypropylene fibers was added to the mortars. The correlations of the twist-off and pull-off results with the compressive and tensile strengths of the reinforced and non-reinforced mortars were determined using linear and power regression analyses. Calibration diagrams were drawn to evaluate the mechanical properties of the reinforced and non-reinforced cement mortars. The effect of fibers on the bond strength between mortar and steel was also evaluated. Finally, the behaviors of the reinforced and non-reinforced mortars in the twist-off and pull-off tests were modeled by the finite element method (FEM) in ABAQUS. The results indicated high consistency between the experimental and numerical results. The fibers had a positive effect on increasing the shear and tensile bond strength between the mortar and steel.

2. Experimental works

2.1. Materials

Portland cement type 2 and sand with a maximum grain size of 4.75 mm were employed. An epoxy resin adhesive was used to glue steel cylinders to the mortar surface in the semi-destructive tests. Table 1 provides the properties of the adhesive. 0.3% volume fraction of polypropylene fibers employed to reinforce the cement mortars. Two mixing ratios were applied to the mortars. A sand/cement ratio of 2:1 was applied to both mortars; however, the water/cement ratios of the first mortar (M1) and second mortar (M2) were 0.4 and 0.5, respectively.

2.2. Samples

Cubic samples with a size of 150 mm were employed for the semi-destructive tests. Also, cubic samples with a size of 50 mm and prismatic samples with a size of 40*40*160 mm were used for the experimental compressive and flexural tests. The samples underwent water-immersion curing after they were taken out of the molds. Then, experimental and semi-destructive tests were performed on the samples at the ages of 3, 7, 42, and 90 days.

To measure the bond strength, first repair mortars were applied on steel plates with dimensions of 200 to 200 and a thickness of 4 mm. In order to observe the effect of fibers on the bond strength between the mortar and steel more clearly, the specimens were kept in water only for seven days and then, they were taken out of it and tested at the ages of 7 and 90 days.

2.3. Experimental methods

To evaluate the mechanical properties, in the twist-off test, a steel cylinder with a diameter of 50 mm was glued on the test surface. Then, a torsional moment was applied to the steel cylinder by a typical torque wrench so it would fail, as shown in Fig. 1a. In the pull-off test, on the other hand, a steel cylinder with a diameter of 50 mm was glued on the mortar surface. Then, a tensile load was applied to the cylinder by a machine so the cylinder would separate from the mortar surface, as shown in Fig. 1b. To measure the compressive strengths of the mortars [21], a mean number of six standard cubic samples with a size of 50 mm were used.

The twist-off, pull-off, and push-out tests were performed to measure the bond strength between the fiber-reinforced mortar and steel. In the twist-off test, a core with a diameter of 50 mm and depth of the repair layer was extracted from the mortar. Afterward, a steel cylinder was attached to the core and subjected to the moment (Fig. 2a). In the pull-off test, the steel cylinder was

Table 1

Mechanical Properties of a Two-component Epoxy Resin Adhesive

Modulus of Elasticity	7-Day Compressive Strength	Shear Strength	Setting Time		Curing Time	
			35ºC	25ºC	35ºC	25ºC
12750 MPa	70 MPa	15 MPa	4 h	10 h	45 min	90 min

a) Twist-off b) Pull-off

Fig. 1 - Evaluate the mechanical properties.

a) Twist-off b) Pull-off c) Push-out

Fig. 2 - Measurement of bond strength.

a) Prism specimens of mortar b) Flexural test apparatus

Fig. 3 - Flexural strength of the mortar.

similarly attached to the core, and the apparatus imposed a tensile force on it (Fig. 2b). In the push-out test, the repair layers were placed around a steel bed, and a jack imposed a force to the steel to separate the mortar (Fig. 2c).

Prism molds with the dimensions 40*40*160 mm were used to measure the flexural strength of the mortars. The flexural strength of the specimens is calculated using Eq. 1 [22].

$$S_f = 2.8\,P \qquad (1)$$

Where,
Sf = the flexural strength (KPa)
P = the maximum load applied (N)
Fig. 3 demonstrates the made prism specimens and the flexural strength measurement apparatus of the mortar.

3. Analyzing the results

3.1. Mechanical properties

3.1.1. The effects of polypropylene fibers on the compressive and flexural strengths

Once a certain content of fibers is added to a mortar, the fibers delay cracks and transfer the stress in the width direction of the cracks, enhancing the strength of the samples and leading the samples to undergo much larger deformations at the maximum stresses. Fig. 4 depicts the compressive behavior of the mortars. As can be seen, the fiber-reinforced mortar resisted a maximum stress of 48.8 MPa at a strain of 0.0142, while the non-fiber reinforced mortar resisted a maximum stress of 46 MPa at a strain of 0.0098, which is approximately 45% smaller than the maximum strain of the fiber-reinforced mortar.

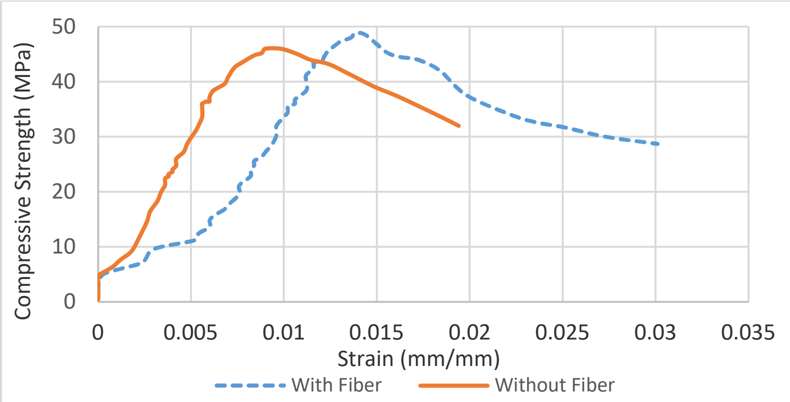


Fig. 4 - The effects of fibers on the compressive behavior of the mortars.

Table 2

The compressive strengths of the mortars (MPa)

		3 Days	7 Days	28 Days	42 Days	90 Days
M1 1 : 2 : 0.4	Non-PP	28.5	40.6	56.2	61	64.7
	+ PP	29.7	42.2	59.1	62.7	66.3
M2 1 : 2 : 0.5	Non-PP	23.3	34.1	47.6	51.2	54.4
	+ PP	24.5	35.8	50.4	53.1	56.6

Table 3

The flexural strengths of the mortars (MPa)

		3 Days	7 Days	28 Days	42 Days	90 Days
M1 1 : 2 : 0.4	Non-PP	7.82	10.12	11.04	11.5	12.08
	+ PP	8.03	10.51	11.31	11.63	12.21
M2 1 : 2 : 0.5	Non-PP	6.7	8.6	9.23	9.71	10.11
	+ PP	6.92	8.85	9.43	9.81	10.27

Table 2 shows the compressive strengths of the mortars with and without fibers at different ages.

According to Table 2, the addition of a 0.3% volume fraction of fibers improved the compressive strengths of the samples. The addition of polypropylene fibers to M1 and M2 led to the mean improvements of 3.7% and 4.8% in the compressive strength, respectively. Also, the comparison of the mortars indicates that M1 with a lower water/cement ratio had a higher compressive strength. Table 3 provides the flexural strengths of the mortars with and without fibers at different ages. According to Table 4, the addition of a 0.3% volume fraction of fibers enhanced the flexural strengths of the samples. The addition of polypropylene fibers to M1 and M2 led to the mean enhancements of 2.3% and 2.1% in the flexural strength, respectively.

Similar results were obtained in another study on the flexural strength of mortars [23]. In the above study, it was found that the flexural strength of 28-day specimens was almost 7% higher compared to the 7-day ones. In the current study, the flexural strength of the mortars M1 and M2 increased by 9% and 7.3%, respectively, in the 28-day specimens compared to the 7-day ones. Furthermore, in the mentioned study, the compressive strength of 28-day specimens was almost 50% higher compared to the 7-day ones. In the current study, the compressive strength of the mortars M1 and M2 increased by 39% and 40% in the 28-day specimens compared to the 7-day ones.

In the mentioned study, the 7-day and 28-day compressive strength equaled 33.7MPa and 50MPa, respectively. In the current study, the 7-day and 28-day compressive strength of the mortars equaled 34.1MPa and 47.6MPa, respectively. Moreover, the flexural strength of the repair mortars in the mentioned study was 6.8MPa and 7.5MPa at the ages of 7 and 28 days, respectively, being equal to 8.6MPa and 9.23MPa in the current study. As can be seen, a slight difference exists between the results.

3.1.2. Twist-off results

This section provides the relationship between the twist-off results and the experimental results of the mortars with and without fibers by the linear and power regression analyses. Table 4 provides the results obtained from twist-off tests on the repair mortars with and without fibers. According to the table, the addition of the fibers increased the results of the twist-off tests on the repair mortars. At the age of 90 days, the addition of the fibers to the repair mortars resulted in a rise in the surface strength of the mortars by almost 4%.

Table 4

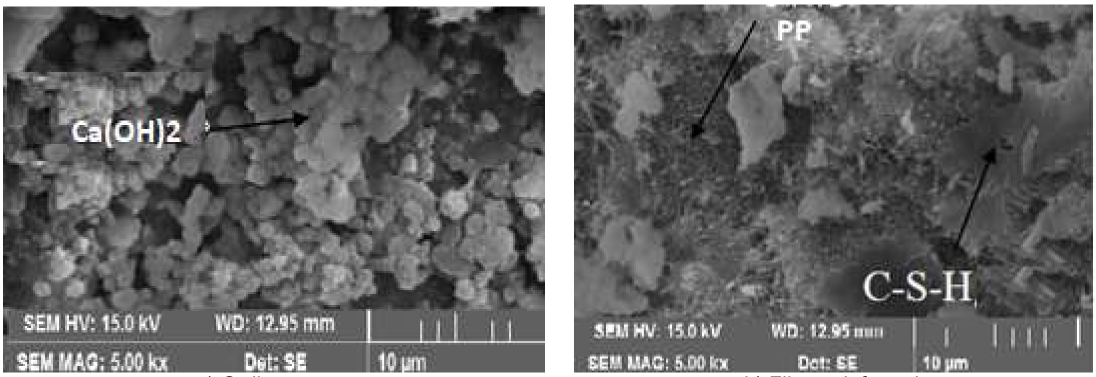
The results of Twist-off method (MPa)

		3 Days	7 Days	28 Days	42 Days	90 Days
M1 1 : 2 : 0.4	Non-PP	4.02	5.99	7.98	8.64	9.28
	+ PP	4.55	6.65	8.47	8.92	9.67
M2 1 : 2 : 0.5	Non-PP	3.90	6.04	7.59	8.26	9.18
	+ PP	4.51	6.58	7.97	8.57	9.56

Table 5

EDX results (weight percentage)

Sample	C	O	Si	Ca	Al	Fe	K	Na	Mg
With Fiber	16.43	46.34	14.49	15.56	3.07	1.64	1.36	0.58	0.53
Without Fiber	13.75	51.31	6.06	25.01	1.27	1.19	0.55	0.34	0.53



a) Ordinary mortar b) Fiber-reinforced mortar

Fig. 5 - SEM images of mortars.

In addition to their physical effect on reducing the width of cracks and increasing the materials' resistance to the applied stresses, the fibers also had indirect chemical effects on the mortars. The EDX (energy-dispersive X-ray spectroscopy) was used for the elemental analysis of the mortar specimens. Table 5 illustrates the results of the EDX analysis.

As can be seen in Table 5, silicon, calcium, and oxygen had high percentages in the spectra of both mortar specimens, and other elements, such as iron, aluminum, carbon, potassium, sodium, and magnesium were also identified in the specimens. By comparing the EDX of the fiber-reinforced and ordinary mortars, it was found that the oxygen molecules in the fiber-reinforced mortar were 46.34% of the total molecules while being 51.31% in the ordinary mortar. Due to the increased shrinkage and presence of more cracks in ordinary mortars, more oxygen entered their void spaces, reacted with some materials inside the mortar, or oxidized them. Therefore, there are lower amounts of silicon and aluminum elements in the ordinary mortar compared to the fiber-reinforced mortar. The outer surface of the mortar is in contact with the outer space and is more sensitive to various changes than the other parts. Thus, the mortar surface is influenced mostly by the entry of oxygen molecules into the mortar. Therefore, the difference between the results of the twist-off test on the mortars with and without fiber can be justified.

The scanning electron microscopy (SEM) images and analyses were used to examine the effect of polypropylene fibers on mortars and investigate the microscopic structure of mortars (Fig. 5).

As shown in Fig. 5(a), the hydrated paste is formed in which the large separate crystals with a polyhedral prismatic form represent calcium hydroxide or portlandite. However, some voids can be seen in the mortar, and failure to complete the cement hydration process may greatly contribute to the reduction in mortar strength. Fig. 5(b) shows that with the addition of polypropylene fibers to the mortar, the processes of cement hydration and formation of C–S–H silica gel beside the polypropylene fibers take place well, making the mortar composition more uniform. In other words, the addition of polypropylene fibers causes the better bond of the mortar.

To examine in detail the phases and crystallographic structure of the particles in the mortar before and after the addition of fibers, the XRD test was performed on the samples, and the results are shown in Fig. 6. It can be observed that with the addition of fibers, the peak intensity of calcium hydroxide ($Ca(OH)_2$) is reduced, which is shown with a black arrow. Since the products of the hydration reaction are hydrated calcium silicate and calcium hydroxide, decreasing the amount of

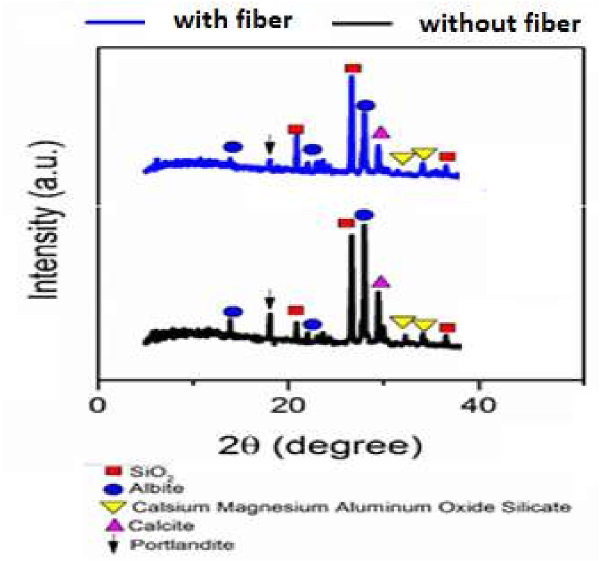
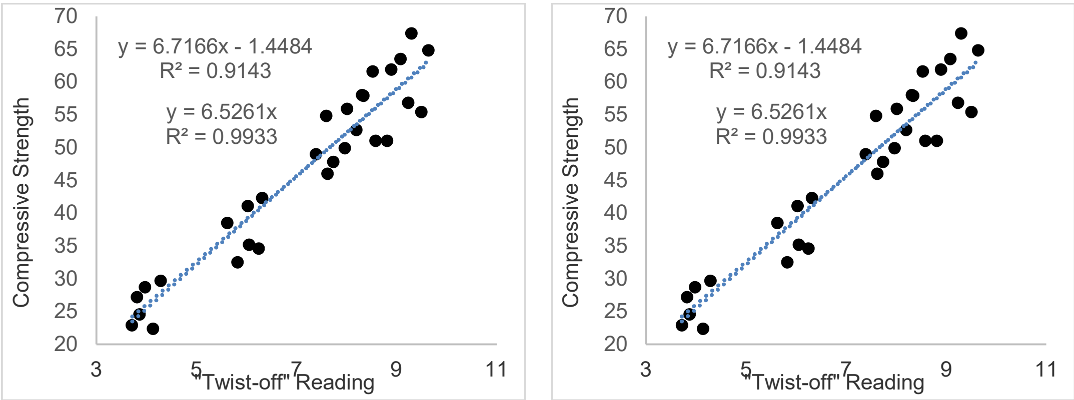


Fig. 6 - X-ray diffraction pattern for fiber-reinforced mortar.

calcium hydroxide increases the hydrated calcium silicate (C–S–H gel). The increase in the hydrated calcium silicate during the hydration process can affect the final properties of mortar and increase the mortar strength.

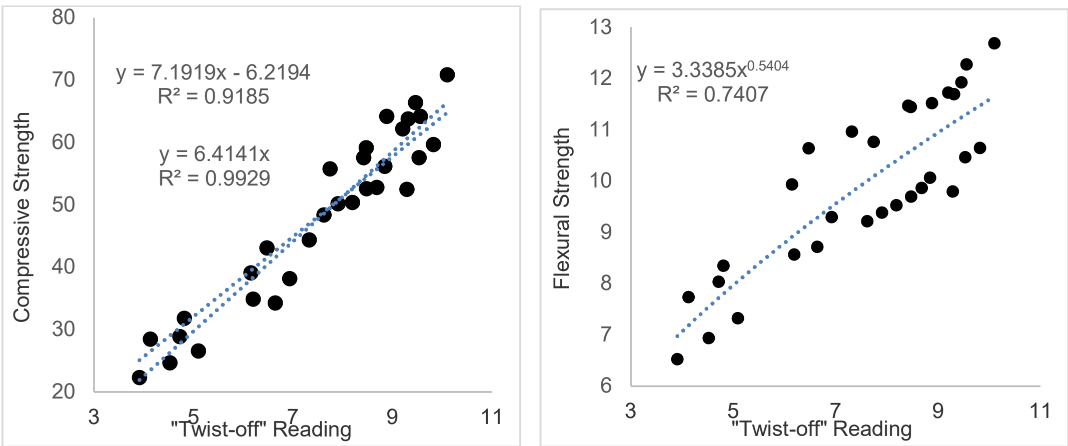
Fig. 7 demonstrates the relationship between the twist-off results and the compressive and flexural strengths of the cement mortars without fibers.

According to Fig. 7a, the linear regression analysis yielded a coefficient of determination of 0.914 between the twist-off results and the compressive strength of the mortar without fibers. However, as can be seen, if the linear regression equation is selected as y=ax to re-perform the correlation analysis, a coefficient of determination of 0.913 is obtained. Considering the small difference between the coefficients of determinations, the twist-off results can be translated into compressive strength values by the linear calibration curve of y=6.526x with a correlation coefficient of 0.955 at a high confidence level. Also, according to the power regression analysis in Fig. 7b, the coefficient of determination and correlation between the twist-off results and compressive strengths of the cement mortars were obtained to be 0.772 and 0.88, respectively. Thus, the twist-off results can be translated into the flexural strength values of the cement mortars by the equation of y=3.379x0.498 at a confidence level of 88%.



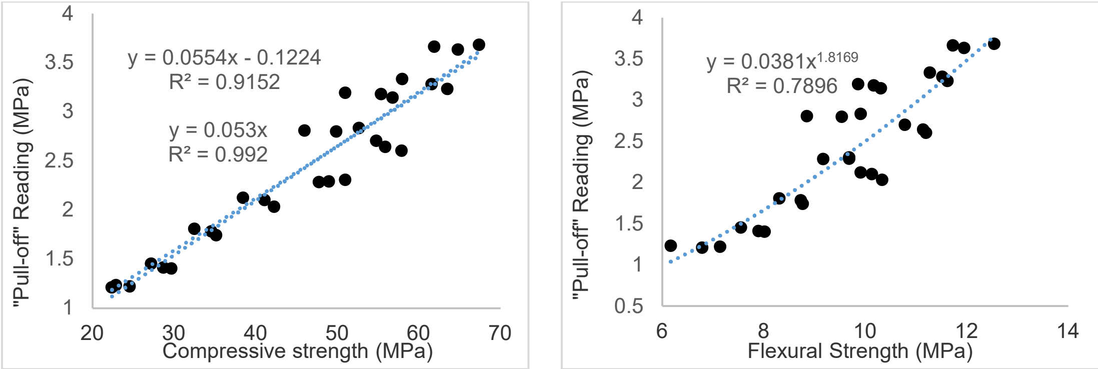
a) twist-off vs. compressive strength b) twist-off vs. flexural strength

Fig. 7 - The correlation between the twist-off results and mechanical properties of the cement mortars without fibers.



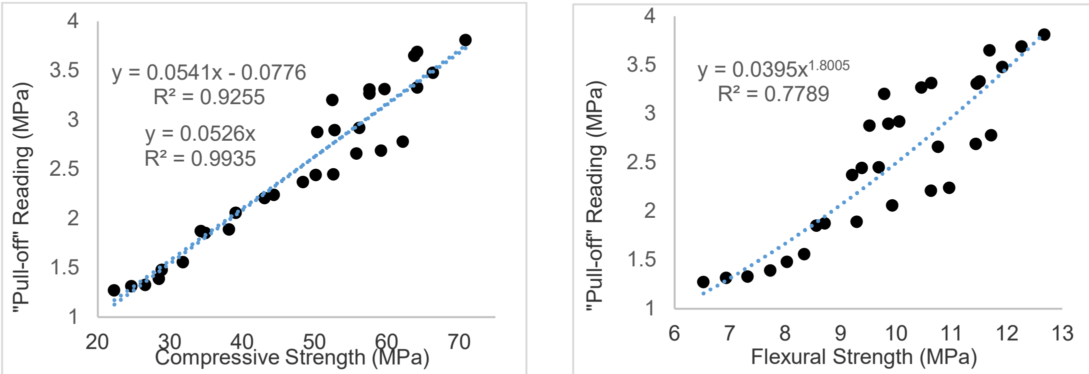
a) twist-off vs. compressive strength b) twist-off vs. flexural strength

Fig. 8 - The correlation between the twist-off results and the mechanical properties of the fiber reinforced mortars.



a) pull-off vs. compressive strength b) pull-off vs. flexural strength

Fig. 9. The correlation between the pull-off results and mechanical properties of the cement mortars without fibers.



a) pull-off vs. compressive strength b) pull-off vs. flexural strength

Fig. 10 - The correlation between the pull-off results and the mechanical properties of the fiber reinforced mortars.

Fig. 8 illustrates the relationship between the twist-off results and the compressive and flexural strengths of the fiber-reinforced cement mortar. According to Fig. 8a, the linear regression analysis yielded a coefficient of determination of 0.919 between the twist-off results and the compressive strength of the fiber reinforced mortars. However, as can be seen, if the linear regression equation is selected as y=ax to re-perform the correlation analysis, a coefficient of determination of 0.907 is obtained. Considering the small difference between the coefficients of determinations, the twist-off results can be translated into compressive strength values by the linear calibration curve of y=6.414x with a correlation coefficient of 0.952 at a high confidence level. Also, according to the power regression analysis in Fig. 8b, the coefficient of determination and correlation between the twist-off results and compressive strengths of the fiber reinforced mortars were obtained to be 0.77 and 0.87, respectively. Thus, the twist-off results can be translated into the flexural strength values of the fiber reinforced mortars by the equation of y=3.338x0.54 at a confidence level of 87%.

3.1.3. Pull-off results

Fig. 9 demonstrates the relationship between the pull-off results and the compressive and flexural strengths of the cement mortars without fibers.

According to Fig. 9a, the linear regression analysis yielded a coefficient of determination of 0.915 between the pull-off results and the compressive strength of the mortar without fibers. However, as can be seen, if the linear regression equation is selected as y=ax to re-perform the correlation analysis, a coefficient of determination of 0.913 is obtained. Considering the small difference between the coefficients of determinations, the pull-off results can be translated into compressive strength values by the linear calibration curve of y=0.053x with a correlation coefficient of 0.95 at a high confidence level. Also, according to the power regression analysis in Fig. 9b, the coefficient of determination and correlation between the pull-off results and compressive strengths of the cement mortars were obtained to be 0.823 and 0.91, respectively. Thus, the pull-off results can be translated into the flexural strength values of the cement mortars by the equation of y=0.038x1.817 at a confidence level of 90%.

Fig. 10 illustrates the relationship between the pull-off results and the compressive and flexural strengths of the fiber-reinforced cement mortar. According to Fig. 10a, the linear regression analysis yielded a coefficient of determination of 0.926 between the pull-off results and the compressive strength of the fiber reinforced mortars. However, as can be seen, if the linear regression equation is selected as y=ax to re-perform the correlation analysis, a coefficient of determination of 0.924

is obtained. Considering the small difference between the coefficients of determinations, the pull-off results can be translated into compressive strength values by the linear calibration curve of y=0.053x with a correlation coefficient of 0.96 at a high confidence level. Also, according to the power regression analysis in Fig. 10b, the coefficient of determination and correlation between the pull-off results and compressive strengths of the fiber reinforced mortars were obtained to be 0.824 and 0.91, respectively. Thus, the pull-off results can be translated into the flexural strength values of the fiber reinforced mortars by the equation of y=0.04x1.8 at a confidence level of 91%.

3.2. Bond Strength

Fig. 11 illustrates the results of the twist-off test used to determine the shear bond strength.

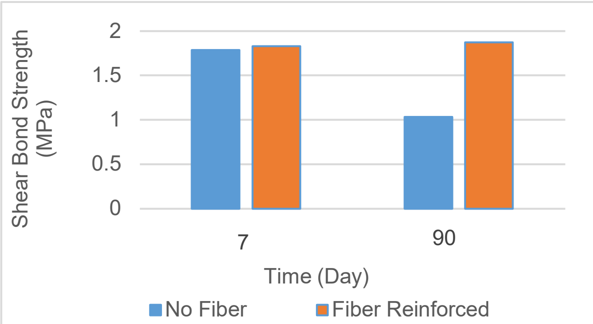


Fig. 11 - Shear bond strength results of the "Twist-off" Test.

As illustrated in Fig. 11, it is observed that adding polypropylene fibers to the mortar significantly increases the shear bond strength of the repair layer with the steel substrate. However, there is little difference between their strength at the age of 7 days when the samples have just been cured and extracted. The addition of fiber to the mortars cured with water increased shear bond strength between the repair mortar and steel substrate to 68.5% at age of 90 day. Compared to mortars without fibers, the increase in shear bond strength of mortar with fibers is due to the increased crack width control and fiber shrinkage.

Fig. 12 illustrates the results of the pull-off test used to determine the tensile bond strength.

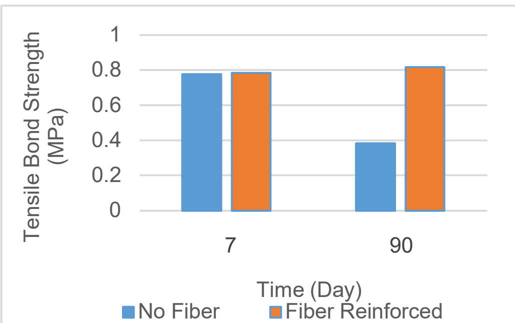


Fig. 12 - Tensile bond strength results of the "Pull-off" Test.

As illustrated in Fig. 12, it was observed that adding polypropylene fibers to the mortar significantly increases the tensile bond strength of the repair layer with the steel substrate. However, there was little difference between their strength at the age of 7 days when the samples had just been cured and extracted. Adding fiber to the mortars cured with water increased the tensile bond strength between the repair mortar and steel substrate to 75.2% at age of 90 day. The improvement in tensile bond strength evident in the mortar with fibers is due to the increased crack width control and fiber shrinkage.

Fig. 13 shows the shear bond strength between the repair mortars (with and without fibers) and the steel bed. As can be seen in Fig. 11.a, the shear bond strength between the ordinary repair mortar and the steel bed, obtained from the push-out test at the ages of 7 and 90 days, was respectively 1.87 and 1.21 MPa. Meanwhile, the shear bond strength between the fiber-reinforced mortar and steel at the ages of 7 and 90 days equaled 1.91 and 1.92 MPa, respectively. It can be seen that the addition of the fibers to the repair mortar increased the 90-day shear bond strength by 50%.

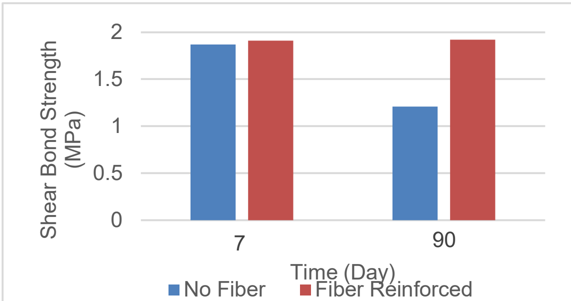


Fig. 13 - Shear bond strength results of the "Push-out" Test.

Overall, the data shown in Figs. 11 to 13 indicate that adding fibers to mortars has a significant effect on the shear and tensile bond strength between the repair mortar and steel substrate, resulting in a general improvement. Experimentally obtained results indicate that most failures occurred at the common surfaces between the repair mortar and steel substrate; and that the composite failure only occurred in a very limited number of samples, and did not occur at the boundaries between the surfaces. Therefore, it has little effect on the results and can be disregarded.

As shown in Figs. 11 to 13, the bond strength between the ordinary mortar and the substrate experiences a sharp drop after 90 days. This is mainly due to the shrinkage in the ordinary repair mortars and the development of cracks, leading to loss of bond. Fig. 14 illustrates the dry shrinkage of repair mortars with and without fibers at different ages. The results indicate that the shrinkage of all mortars starts after leaving the curing practices. Over time, the shrinkage of mortars increases. The process of shrinkage is accelerated because the moisture outflow from the mortar, the outflow of free water from mortar and then the outflow of adsorbed water during the week of curing practices. Fig. 14 demonstrates that the addition of polypropylene fibers to mortars reduced dry shrinkage. Therefore, the mean 90-day shrinkage of mortars containing polypropylene fibers was 14.3% lower than mortar without fibers.

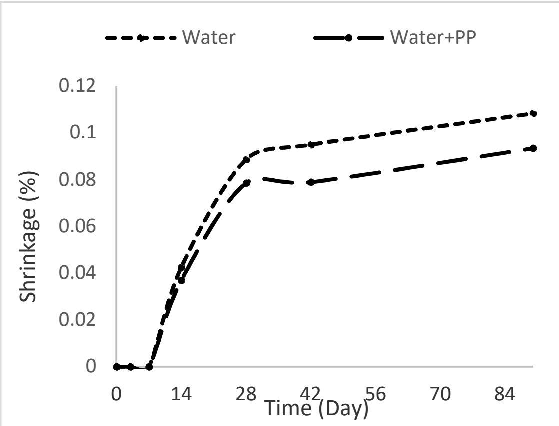


Fig. 14 - Dry shrinkage of mortars.

3.3. Analyzing the pull-off and twist-off tests by the finite element method

The mortar cubes were meshed by a combination of C3D8R and C3D4 elements to evaluate the behavior of the samples under the pull-off and twist-off tests. The main parts of the samples were meshed by eight-node reduced-integral cubic elements of C3D8R. Also, convergence was performed for meshes with the sizes of 0.5, 1, and 2 mm, selecting the 1-mm elements for the meshing. The side parts of the samples were meshed by continuous tetrahedral four-node elements with the minimum and maximum sizes of 1 mm and 15 mm in the joints with the main elements and in the lateral locations, respectively. The adhesive was meshed with 2-mm C3D8R elements, while the steel cylinder was meshed by 2-mm elements. The elements of the steel cylinder were selected to be of a size of 10 mm in the axial direction. Fig. 15 depicts meshing.

The behaviors of the mortars with and without fibers were employed to model the twist-off and pull-off tests in ABAQUS. According to Table 2, the fiber-reinforced mortar had a compressive strength of 50.4 MPa at the age of 28 days, while the non-reinforced mortar had a compressive strength of 47.6 MPa. The twist-off results of the fiber-reinforced and non-reinforced mortars were obtained to be 180 N.m and 190 N.m, respectively. Also, the pull-off results of the fiber-reinforced and non-reinforced mortars were obtained to be 4750 and 4500 N, respectively.

Fig. 16 shows the twist-off test results. As can be seen, initial cracks occurred in the side locations of the samples as they underwent the largest moment. The failure of the non-reinforced cement mortar began at a moment of 125 N.m. As the moment increased, the failure grew. The ultimate failure occurred at a moment of 177 N.m. The failure of the fiber-reinforced mortar, on the other hand, began at a moment of 139.4 N.m. The ultimate failure happened at a moment of 185 N.m. As can be seen, the failure of the fiber-reinforced mortar occurred at a larger moment. Also, the comparison of the experimental results to FEM

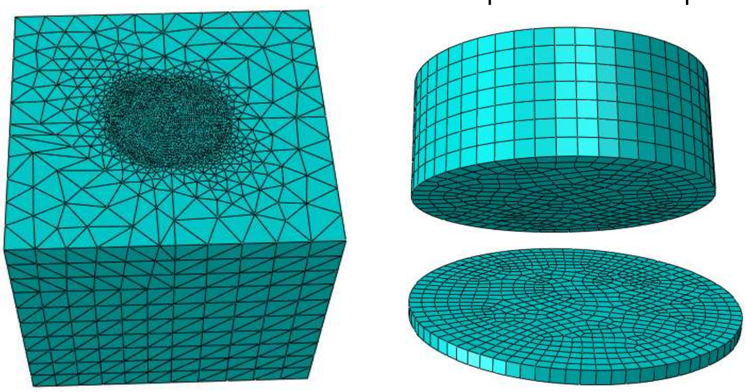
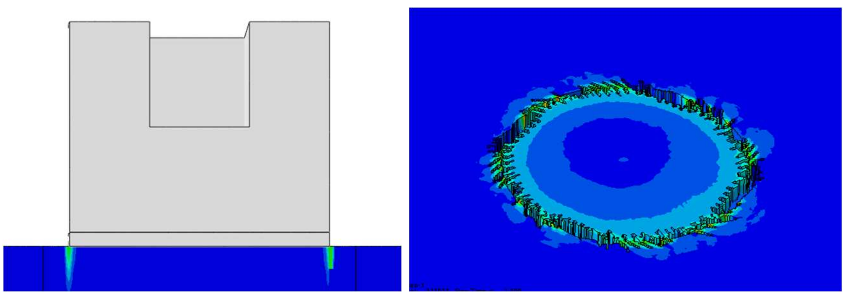
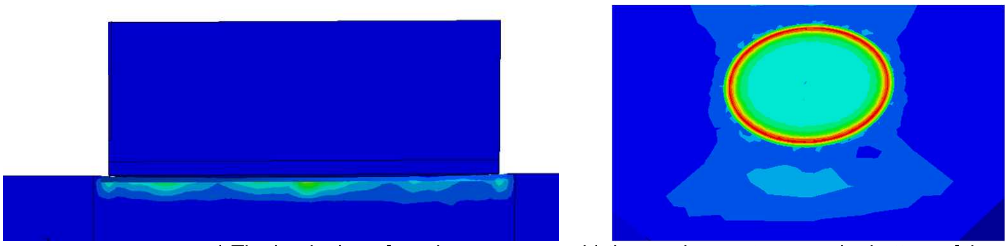


Fig. 15 - The meshing of the model.



a) The beginning of cracks b) failure

Fig. 16 - The twist-off test.



a) The beginning of cracks b) the maximum stress on the bottom of the cylinder

Fig. 17 - The pull-off test.

results suggest high consistency between the experimental and numerical results.

Fig. 17 represents the pull-off test results. As can be seen, for the non-reinforced mortar, cracks began at a load of 2248 N in the bottom of the cylinder. For the fiber-reinforced mortar, on the other hand, initial cracks occurred at a load of 2701 N. The non-reinforced mortar reached a critical load of 4555 N, while the fiber-reinforced mortar resisted up to 4905 N. As can be seen, fiber reinforcement improved the behavior. Also, high consistency exists between the numerical and pull-off results.

4. Conclusion

- The analysis of the SEM images revealed that with the addition of polypropylene fibers to the mortar, the process of cement hydration and formation of C-S-H silicate gel, along with polypropylene fibers, was conducted well and resulted in better homogeneity of the mortar mix. As a result, the flexural and compressive strength of the fiber-reinforced mortars were 2.2% and 4.2% higher than the ordinary ones.

- The shrinkage of the ordinary mortars was almost 14.3% more compared to the fiber-reinforced ones. Therefore, a remarkable decrease was observed in the bond strength between the ordinary mortar and steel substrate after 90 days.

- The 90-day shear and tensile bond strengths between conventional mortars and steel from Twist-off, Push-out and Pull-off tests are 0.98, 1.21 and 0.4MPa, respectively. The three mentioned values between fiber-reinforced mortars and steel have demonstrated 75.1, 59 and 94.1 percent increase, respectively.

- The analysis of the XRD results indicated an increased amount of hydrated calcium silicate in the fiber-reinforced mortars. This rise through the hydration procedure can affect the ultimate properties of the mortar and increase its strength.

- The analysis of the EDX results showed that the oxygen molecules inside ordinary mortars were more compared to the fiber-reinforced ones. In fact, due to more shrinkage and more cracks in the ordinary mortars, more oxygen entered the void spaces of the mortar surface. This is one reason for the difference between the results of twist-off tests on the ordinary mortars and fiber-reinforced ones.

- Given the high Correlation between the experimental results and the twist-off and pull-off results, these semi-destructive tests can be employed to evaluate the in-situ strengths of mortars.

- The results obtained from the numerical modeling of the twist-off and pull-off tests indicated delayed appearance of cracking and higher load resistance in the fiber-reinforced mortars.

- The results indicated high consistency between the experimental results and numerical twist-off and pull-off results obtained in ABAQUS.

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