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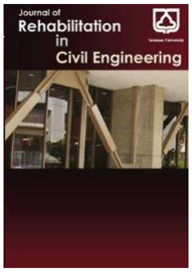

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Bond Strength of Fiber-Reinforced Mortar and Concrete Interface under Pre-Stress

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ABSTRACT

Shrinkage and improper compaction of the repair layer are among the main reasons for the adhesion drop. Shrinkage results in cracking and improper compaction causes fine pores in the interface. Due to the fact that shrinkage and non-compacting are the main reasons for reducing strength and adhesion, therefore, in this paper, research has been done in this regard. The present study aimed to investigate the effect of polypropylene fibers on the shrinkage of mortars and bond of mortar/concrete interface. Moreover, the impact of diverse pre-stresses on the adhesion between mortar and concrete was evaluated by imposing pre-stresses on fiber-reinforced mortars. Adhesion was assessed by the “twist-off” and “pull-off” tests. Furthermore, the effect of fibers and pre-stress on the adhesion examined using SEM images and X-ray diffraction. It is necessary to assess the compressive strength of concrete and mortar in the field. Therefore, the aforementioned semi-destructive methods were employed to investigate the in-situ compressive strength of mortars at different ages. For this purpose, the correlation coefficient between the in-situ and laboratory methods was defined and the scaling curves were plotted to convert the in-situ test results into compressive strengths of the mortars. The obtained findings indicated the positive effect of pre-stress on adhesion. In addition to their mechanical effect, the indirect effect of fibers on the chemical properties of the mortars reduces shrinkage and augments adhesion. Moreover, given the great relationship among the conclusion of “pull-off” and “twist-off” methods, the cost-efficient and available twist-off apparatus can be used for adhesion measurement instead of the costly and import pull-off apparatus. Adding 0.3% of polypropylene fibers to the mortars enhanced the bond strength by 76.8% and 41.7%, respectively and reduced the shrinkage of the mortars by 11%. An initial stress of 0.5 kg/cm^2 increased the shear and tensile bond strength at the age of 90 days by 12.8% and 13.3%, respectively.

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1. Introduction

Suitable compaction of a repair mortar applied to the concrete substrate is a factor that influences the enhancement of adhesion between the mortar and concrete. The mortar-concrete interface is of great importance since unsuitable compaction would induce fine holes on the interface and contribute to the reduction of the bond strength. In a study on the result of compaction operations on the strength of self-compacting concrete, it was observed that proper compression increases the compressive strength of concrete by about 5% [1]. In another study evaluating the strength of different compacted concretes, it was concluded that the compressive strength results of the Schmidt, Ultrasonic and Extraction hammer tests are highly influenced by the method of compaction and compaction [2]. Also, in another research on the effect of compression on the strength of ordinary concretes, it was found that the appropriate density increases the compressive strength between 4 to 8 MPa [3].

As the most used construction materials, both concrete and mortars are brittle, heterogeneous, and anisotropic, unlike steels. Cement materials exhibit different behavior under tension and compression; they have significantly larger compressive strength. The use of fibers is an effective method for enhancing the ductility of concrete and mortars. Fibers improve the behavior of concrete under compressive stresses [4, 5] and have a positive effect on the stress-strain curve [6]. Shakir et al. [7] found that the addition of fibers at a volume fraction of 0.005 increased the tensile strength of the mortar by nearly 7.21%. Mesbah et al. [8] studied the effects of polypropylene fibers on mortar cracks. They observed that the addition of propylene fibers to the mortar delayed cracks and prevented crack opening. Sadrmomtaz et al. [9] explored the influences of polypropylene fibers on mortars. They concluded that polypropylene fibers improved the compressive and flexural strength of the mortars. However, a rise in the fiber volume fraction above 0.003 had a negative effect on the mortars. Numerous studies concluded that the addition of an excessive volume fraction of fibers negatively impacts the properties of cement materials [10-12].

Furthermore, new and non-mineral composite materials have been utilized to improve the behavior and adhesion of mortars in recent years. Fiber-reinforced polymers and fiber-reinforced cement matrixes have been successful in strengthening and repair due to their advantages over traditional materials. Ease of use and high strength/weight ratios are among the major factors in the success of such new technologies [13]. Glass fiber-reinforced polymers are another material that can be employed in, for example, the strengthening of columns in reinforced-concrete structures [14]. Steel-reinforced grout (SRG) is a new repair material that improves concrete surface adhesion [15].

The present study applied different initial compressive loads to polypropylene fiber-reinforced repair mortars and evaluated their effects on tensile and shear adhesion strength among the repair materials and substrate by using the "pull-off" and "twist-off" methods. Also, to measure the compressive strength of the mortars, semi-destructive in-situ tests were employed. Earlier studies on the compressive strength measurement of repair materials were mostly conducted by using destructive methods in experimental settings. However, experimental tests suit only particular conditions. Thus, some factors, including real-life operations, non-consideration of curing type, moisture, and the temperature difference cannot represent mortars that are used in different parts of a structure. The strength of mortars can be calculated using destructive, semi-destructive, and non-destructive tests. Non-destructive tests include the Schmidt hammer [16] and ultrasonic [17] tests. However, such tests obtain strength indirectly. Destructive tests, such as the core drilling [18] and pull-out [19] test, are limited as they are not repeatable and cause damage. However, the research has shown that the compressive strength of a drilled core is lower than that of the actual compressive strength [20]. Semi-destructive tests, such as the friction-transfer [21], “twist-off” [22], and “pull-off” [23] tests, yield more valid results than those of non-destructive tests as rapture occurs within the test piece.

In some researches, friction transfer, “pull-off” and “twist-off” methods have been used to determine the bond strength between different types of mortars and concrete substrate. In a research, the adhesion between plain mortar and substrate concrete was studied using various curing procedures. It was observed that curing for one week has a slight positive effect on long-term adhesion [24]. A study on the impact of SBR polymer on mortar-concrete adhesion showed that adding 15% polymer increases the adhesion after 90 days by 2.5 times [25-26]. Using the friction-transfer test, another research showed that a lack of curing at high ages causes the repair mortar to separate from the substrate concrete [27-28].

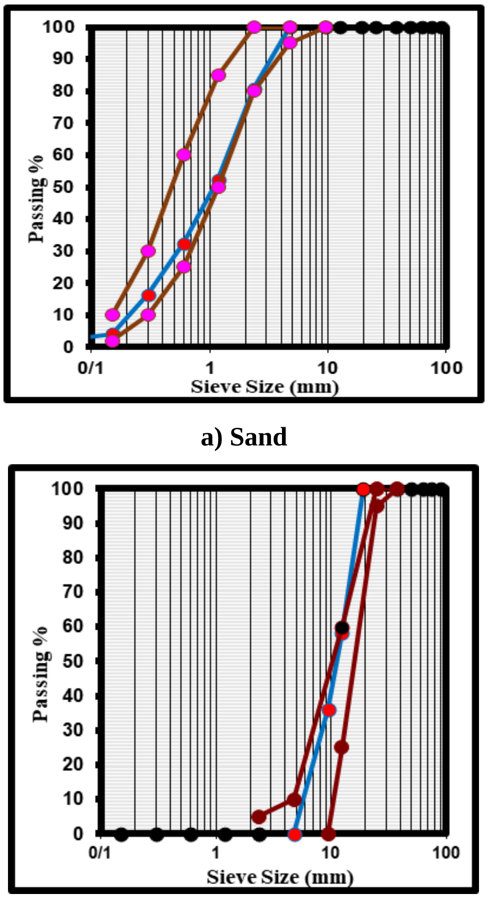
The results of different tests indicated that adding polypropylene fibers to repair mortar increases the adhesion between repair mortar and steel by about 90% [29-31]. Another research used the friction-transfer test to show that the addition of fibers increases mortar-concrete adhesion by about 50% [32]. Moreover, numerous papers have validated new twist-off and friction-transfer tests by modeling them in finite element software. Moreover, the results obtained from these tests have been compared with those of standard methods, indicating the high accuracy of the results of the above tests [33-38]. As discussed above, there are various methods of enhancing adhesion between repair mortar and concrete substrates. The present paper simultaneously uses polypropylene fibers and applies a pre-stress to the mortar for this purpose. The pre-stress is useful when the mortar layer is thin and compaction is difficult.

In this study, the effects of pre-stresses on the bond strength among the fiber-reinforced mortars and the concrete substrate were evaluated by the “pull-off” and “twist-off” methods. Also, the effects of fibers on the shrinkage, tensile and shear adhesion strength, of the mortars were explored in in-situ methods and at different curing ages. Equations were proposed to translate in-situ findings into experimental results by measuring the correlation coefficient and calibration plots.

2. Experimental Works

2.1. Materials

Type II cement was employed. The grading of the gravel and sand was performed according to the ASTM-C136 [39]. The densities of the gravel and sand in a saturated condition with dried surfaces were obtained to be 2330 and 2510 kg/m^3, respectively. Also, the water absorption of the gravel and sand was determined to be 2.6% and 3.2% according to ASTM C127 [40] and ASTM C128 [41] Standards, respectively. Fig. 1 illustrates the grading of aggregates.



a) Sand

b) Gravel

Fig 1. Gradation chart.

Table 1. reports the weight ratios employed in the substrate concrete.

Table 1. Concrete substrate weight ratios (Kg/m^3)

Super plasticizer	W/c	Water	Gravel	Sand	Cement
2.6	0.36	190	664	835	530

A two-part epoxy adhesive was employed at a volumetric ratio of 1:1 to stick steel cylinders on the mortar surface in the "pull-off" and "twist-off" methods. Table 2 provides the mechanical properties.

Table 2. Epoxy adhesive specifications[1]

Setting time		Shear strength	compressive strength	Modulus of elasticity
25 °C	35 °C			
10 h	4 h	15 MPa	70 MPa	12750 MPa

Regarding the mix design of mortars, most books and standards [42-43] mention that cement mortars consist of a mixture of specific ratios of sand, cement, and water, where the sand-to-cement ratio varies from 2:1 to 6:1. Moreover, the water-to-cement ratio is about 0.5. In addition, a sand-to-cement ratio of 3:1 has been used in most standards to measure some characteristics of mortars, such as shrinkage. Hence, we decided to use mortar with a sand-to-cement ratio of 3:1. Furthermore, the fiber-reinforced mortar was prepared by adding a 0.3 volume fraction of polypropylene fibers to the mixture according to the step-by-step procedure of the Iranian National Concrete Mix Design [44]. To prepare the substrate concrete, we decided to use concrete with relatively high strength in order to minimize fracture in the substrate since the aim was to achieve pure adhesion strength between the mortar and concrete. Due to the high accuracy of the methods used herein, these tests can be applied also to other materials.

A ratio of sand/cement 3:1 and a w/c ratio of 0.5 were applied to the repair mortars. Polypropylene fibers were employed for reinforcement at a volume fraction of 0.003. The properties of polypropylene fiber are shown in Table 3.

Table 3. Fibers specifications[2]

Diameter (mm)	Length (mm)	Modulus of Elasticity (GPa)	Tensile Strength (MPa)	Special Weigth (g/cm^3)
0.022	12	7	380	0.91

The reason for using polypropylene fibers is that these fibers are found in abundance in Iran. Also, its price is cheaper than other fibers. In order to be able to use the results of this research for practical work in different

[1] The properties of the epoxy resin were procured from the manufacturer.

[2] The properties of the fibers were procured from the manufacturer.

parts of the country, it was decided to use a type of fiber that is available everywhere and has a low price. Of course, it should be mentioned that there are other fibers that can improve the shrinkage and adhesion between the layers.

2.2. Making Samples

To measure the adhesion between the fiber-reinforced mortar and bed concrete, 25mm thick mortars were applied to the substrate concrete surface. Then, the compressive loads of 0.1, 0.5, 5, and 10 kg/cm^2 were applied to the mortars by using 25, 100, 1100, and 2250kg weights for 24 hours, respectively. The compressive loads of 5 and 10 kg/cm^2 were applied using a concrete breaker, while the compressive loads of 0.1 and 0.5 km/cm^2 were added by hands, as shown in Fig. 2. The samples were curing in the water for seven days and then released until the test time. The tests were performed at the ages of 7, 42, and 90 days.

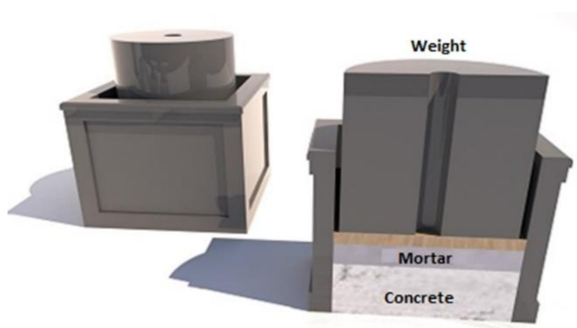


Fig 2. Initial compression on the mortar surface.

Furthermore, standard experimental specimens were fabricated and molded for 24 hours to measure the compressive strength of fiber-reinforced mortars. Then, they were demolded to be kept in the water until the test time. At the same time, the specimens required for the compressive strength evaluation of the mortars by semi-destructive tests were placed in the water.

The prepared samples consist of 40 prismatic samples to measure the shrinkage, 54 samples to measure the shear adhesion strength, 54 samples to measure the tensile adhesion strength, 48 samples to evaluate the compressive strength, and 108 samples to be used as the concrete substrate.

2.3. Experimental Methods

To measure the compressive strength of the materials by using the “twist-off” method, steel cylinders with a diameter of 50 mm were attached to the test surface. Then, a typical torque meter was utilized to apply a torsional torque to the steel cylinder so that it would separate from the mortar, as shown in Fig. 3a. Also, to measure the compressive strength of the materials using the “pull-off” method, a steel cylinder was attached to the material surface. Then, a tensile load was applied to the cylinder by using a machine so that the cylinder would separate from the mortar surface, as illustrated in Fig. 3b.

a) “Twist-off” method.

b) “Pull-off” method.

Fig 3. Compressive strength evaluation of the mortars.

First, cube-shaped concrete samples with 150-mm sides were prepared as substrate (Fig. 4). Then they were cut using a concrete cutter (Fig. 5). This provided a smooth and strong surface that minimized mechanical interlock at the mortar/concrete interface. Then, the substrate concrete was placed in molds, and a hard water-cement slurry was applied to the saturated and droplet-free concrete surface and was allowed to dry before the repair mortar was applied (Fig. 6).

Fig 4. Substrate concrete.

Fig 5. concrete cutter.

Fig 6. hard water-cement slurry.

To measure the shear adhesion strength among repair layers and concrete surfaces by using the “twist-off” test, Then it is required to drill a core on the repair surface at a depth of nearly 5 cm into the concrete bed. Then, a steel cylinder is attached to the core. A typical torque meter is employed to apply torsional moments to the steel cylinder so that the core undergoes fracture (Fig. 7a). Based on the ultimate torsional moment, the bond of the mortar is calculated using the communication among the shear stress τ and torsional torque T as Eq. (1).

$$\tau = \frac{Tr}{J} \quad (1)$$

Where r is the steel cylinder radius, while J is the second moment of area. To measure the tensile adhesion strength by using the “pull-off” test, a core with a diameter of 5 cm is drilled into the concrete. Then, a steel cylinder with a diameter of 5 cm is attached and pulled by a machine until it fractures, as shown in Fig. 7b. The tensile stress on the contact area among the mortar and concrete is resulted as Eq. (2).

a) “Twist-off” method.

b) “Pull-off” method.

Fig 7. Bond strength measurement.

$$\sigma = \frac{F}{A} \tag{2}$$

Where F is the tensile load, while A is the interface area.

Twist test theory

Given that the core created in the twist-off method is cylindrical with a circular cross section, the shear stresses due to the torsional moment appear normal to the radius, as shown in Fig. 8. The shear stresses are proportional to the distance from the center with the highest shear stress on the perimeter of the circle, which is furthest from the center.

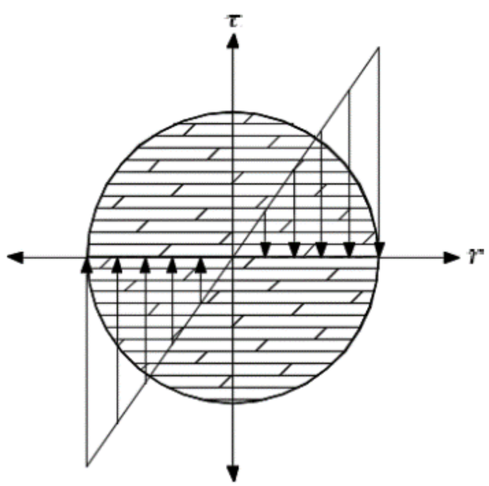


Fig 8. Shear stress created.

According to Mohr's circle, the shear, tensile, and compressive stresses are at most equal to the radius of this circle. In addition, the principal tensile and compressive stresses lie at an angle of 45° with respect to the horizon. Brittle materials, such as concrete, undergo fracture under tension. As shown in Fig. 9, the fracture planes in this case are normal to the direction of tension. Since the highest shear stress is at the perimeter of the circle, fracture can occur as shown in Fig. 10.

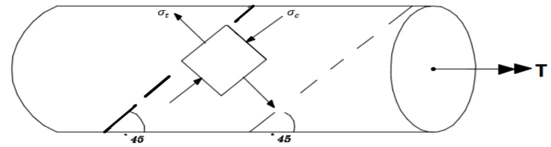


Fig 9. Fracture planes.

Fig 10. Fracture of sample.

The shrinkage of the specimens was calculated according to the ASTM-C157 standard [45] and ASTM-C490 standard [46]. The prismatic shrinkage molds had a area-section of 25*25 mm and 285 mm height. Dry shrinkage is calculated as Eq. (3).

$$L = \frac{L_x - L_n}{G} \times 100 \tag{3}$$

Where L is the length variation, L_x is the difference between the ultimate length and the reference one, L_n is the difference between the initial length and the reference one, and G is the reference length. To evaluate the compressive strength of the mortars according to the ASTM C109 Standard [47], six standard cubic specimens with a size of 50 mm were employed.

In summary, in this paper, experiments have been performed according to the flowchart of Table 4.

Table 4. flowchart of the experimental section.

Experimentals									
Bond strength							Compressive strength		
twist-off test			pull-off test				twist-off	pull-off	Push Jack
Plain mortar	Fiber mortar	Pre-stress mortar	Plain mortar	Fiber mortar	Pre-stress mortar		Plain and fiber mortar		
Comparison of results and methods			Comparison of results and methods				Comparison of results and methods		

3. Results and Analyses

3.1. Shear Adhesion Strength Results of "Twist-Off"

Fig. 11 illustrates the shear adhesion strength among the polypropylene fiber-reinforced repair mortar and substarte in the "twist-off" test at different initial compressive loads.

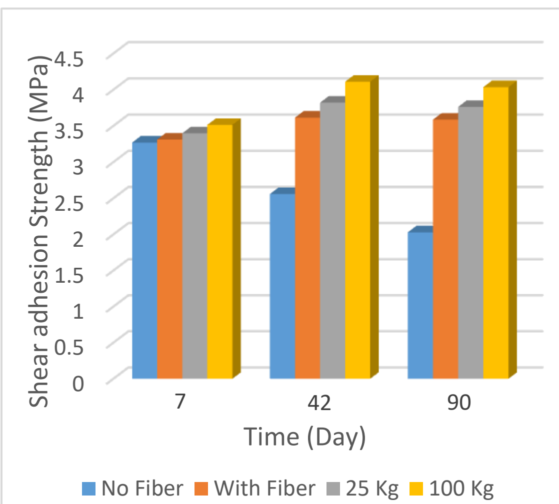


Fig 11. Shear adhesion strength.

As can be seen, fibers improved the shear adhesion strength among the mortars and substrate in the "twist-off" method. The addition of fibers increased the shear bond strength by 41% and 76.8% at the ages of 42 and 90 days, respectively. Also, an initial compression of 0.1 kg/cm^2 enhanced the shear adhesion strength among the mortar and concrete in the "twist-off" method at different ages. However, the increase in the shear bond strength was not significant at this initial compression. The shear bond strength was found to be 3.31, 3.61, and 3.58 MPa at the ages of 7, 42, and 90 days, respectively, in the absence of initial compression. On the other hand, it was observed to be 3.39, 3.82, and 3.76 MPa under an initial compression of 0.1 kg/cm^2 at the aforementioned ages, respectively. As can be seen, an initial compression of 0.1 kg/cm^2 enhanced the shear bond strength by 2.4%, 5.8%, and 5% at the ages of 7, 42, and 90 days, respectively. Furthermore, an initial compression of 0.5 kg/cm^2 raised the shear bond strength by 6.1%, 13.5%, and 12.8% at the ages of 7, 42, and 90 days, respectively .

The increased shear adhesion strength among the fiber-reinforced repair mortar and concert under initial compression can be attributed to larger compaction under compression since the compaction of the repair layer is an important factor in adhesion. Also, initial compression makes the mortar particles more likely to meet the concrete surface, enhancing the shear bond strength. However, no positive effects were observed on adhesion at high initial compressive loads (i.e., 5 and 10 kg/cm^2). An explanation could be grout drainage under high compression. The authors attempted to prevent grout drainage but did not succeed.

3.2. Tensile Adhesion Strength Results of "Pull-Off"

Fig. 12 shows the tensile adhesion strength among the polypropylene fiber-reinforced repair mortar and concrete in the pull-off test at different initial compressive loads.

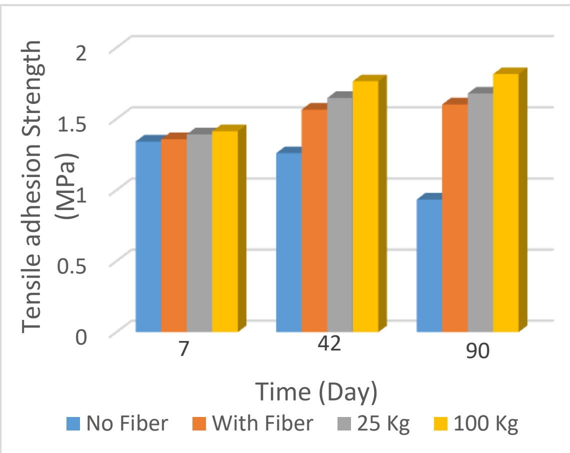


Fig 12. Tensile adhesion strength.

As can be seen, fibers improved the tensile adhesion strength among the mortars and concrete in the "pull-off" method. The addition of fibers increased the tensile bond strength by 23.8% and 41.7% at the ages of 42 and 90 days, respectively. Also, an initial compression of 0.1 kg/cm^2 enhanced the tensile adhesion strength among the mortar and concrete in the "pull-off" method at different ages. However, the increase in the tensile adhesion strength was not significant at this initial compression. The tensile adhesion strength was found to be 1.36, 1.56, and 1.6 MPa at the ages of 7, 42, and 90 days, respectively, in the absence of initial compression. On the other hand, it was observed to be 1.39, 1.64, and 1.68 MPa under an initial compression of 0.1 kg/cm^2 at the aforementioned ages, respectively. As can be seen, an initial compression of 0.1 kg/cm^2 enhanced the tensile bond strength by 2.5%, 5.2%, and 4.8% at the ages of 7, 42, and 90 days, respectively. Furthermore, an initial compression of 0.5 kg/cm^2 raised the tensile bond strength by 4.1%, 12.7%, and 13.3% at the ages of 7, 42, and 90 days, respectively .

One of the most dominant bond strength theories is the theory of physical absorption. This theory plays a significant role in the adhesion strength among mortar and concrete, and is based on intermolecular polar and hydrogen forces. Based on this theory, a better bond is achieved when the desired surface is moistened as adequately as possible, and the bond adhesive, which is the cement paste in this case, reaches all areas of the surface. Thus, in order for the moisturizing process to transpire better, the adhesive must have a lower surface tension force than the critical surface tension of the intended material. This being the case, the bond adhesive can be more easily spread on the surface of the material, and the adhesive will flow into the cavities and gaps of the surface layer.

The most ideal dispersion of the bond adhesive (the cement paste in this case) on the surface on the solid material (the surface of the concrete substrate in this case) is determined by the contact angle criterion [48]. This criterion has been indicated in Fig. 13.

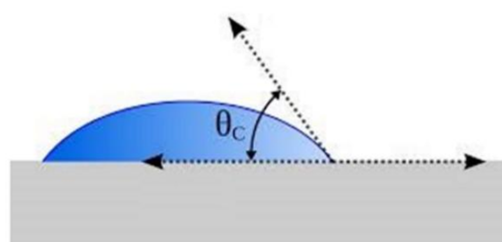


Fig 13. Liquid and solid contact angles [48].

The smaller the θ angle is, the lower the level tension of the fluid will be compared to the solid surface. In other words, liquid has a higher tendency to flow on the surface of the solid. This concept is more evident in Fig. 14.

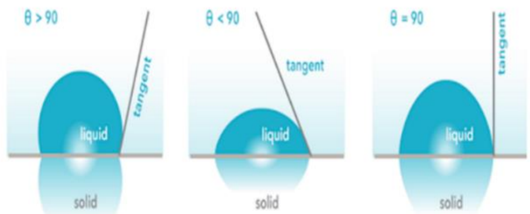


Fig 14. Contact angle and liquid broadening [48].

Based on Fig. 14, the middle liquid has a smaller contact angle, and thus, can provide better surface moisturizing and create a better bond strength. In terms of the concept of contact angle, it can be recognized that the less viscous the cement mortar is, the lower its surface tension, and the more fluid it is, the better it moisturizes the surface of the concrete substrate. This ultimately enhances the bond strength. Accurate measurement of the contact angle parameter, and consequently, the physical adsorption is not possible as a result of the heterogeneity and porosity of the mortar and concrete. Thus, no definitive comments can be made. As observed, applying pre-compress on the repair mortar that has not yet hardened increases the adhesion strength among the repair mortar and the substrate surface. One of the reasons for this is due to higher density and greater contact area of the repair mortar components with the concrete surface.

Scanning Electron Microscopy (SEM) imaging was utilized in order to investigate the cavities in the mortar due to the lack of compaction of the mortar. Fig. 15 indicates the areas related to mortar.

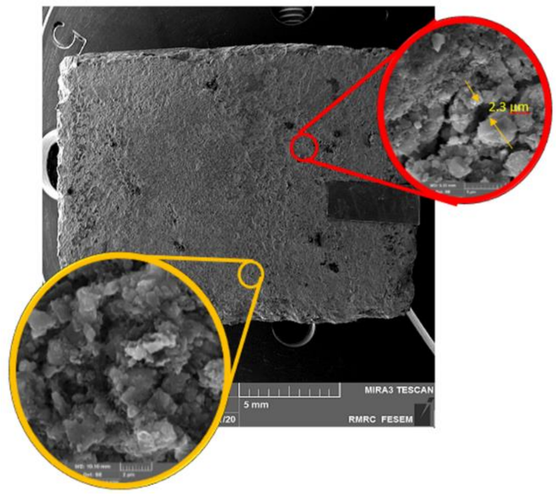


Fig 15. The microscopic image of the mortar.

According to what may be observed in this figure, macro-cavities are observed on the surface of the mortar. These are the result of improper compaction, water evaporation, and concrete & mortar shrinkage. The existence of such cracks can minimize the mechanical and physical properties of the composite. In the magnified image of the mortar, numerous and sizeable cracks can be observed in the structure of the material. The crack width was evaluated using the Image J software, and its value was equal to approximately 2.3 micrometers. The presence of these micro-cracks in the mortar structure can result in stress concentration, and thus, adversely affect the physical and mechanical properties of the system. Such porosities, and lack of proper mixing of the mortar and concrete could be considered as the most significant factor in reducing the bond strength in this sample.

3.3. The Correlation Among the Results Obtained From the "Pull-Off" and "Twist-Off" Methods

Fig. 16 shows the correlation among the results from the "pull-off" and "twist-off" methods. In this figure, each point represents the average of three measurements.

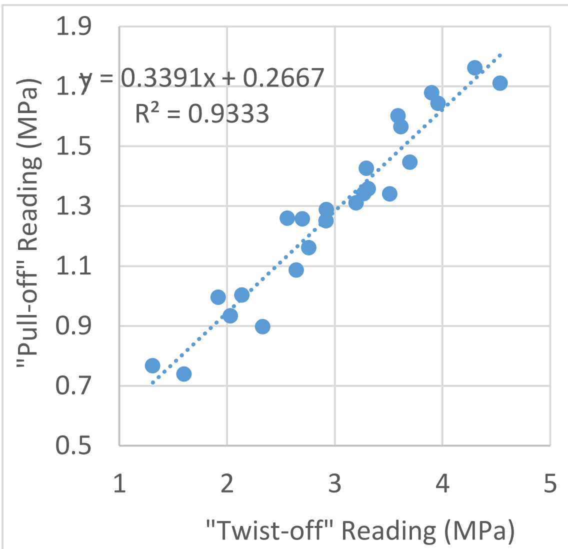


Fig 16. The correlation among the results obtained from the "pull-off" and "twist-off" methods.

According to Fig. 16, the coefficient of correlation and determination among the results obtained from the "pull-off" and "twist-off" methods were 0.96 and 0.93, respectively. Given the great correlation among the results of the mentioned methods, the results of one of them can be obtained using those of the other. Moreover, in determining the adhesion among the mortar and substrate, due to the simplicity and low price of the twist-off apparatus, this method can replace the pull-off method, whose equipment is expensive and requires continuous calibration.

3.4. Dry Shrinkage

Fig. 17 shows the shrinkage results of the repair mortars. According to Fig. 17, the 90-day shrinkage for the mortar without fibers is equal to 0.0822%. By adding fibers to this mortar, it became 0.0720%. The addition of the fibers to the mortar reduced the 90-day shrinkage by 11.1%, on average.

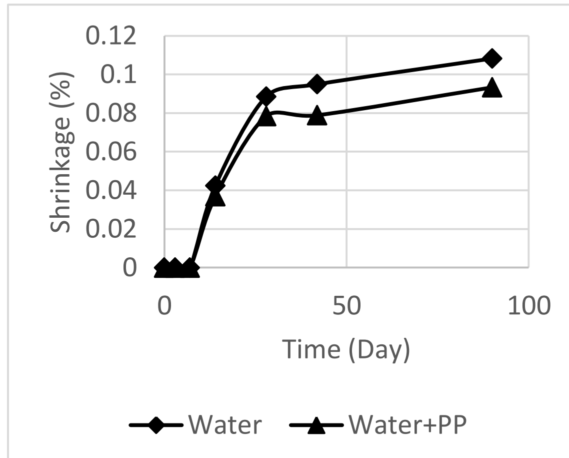
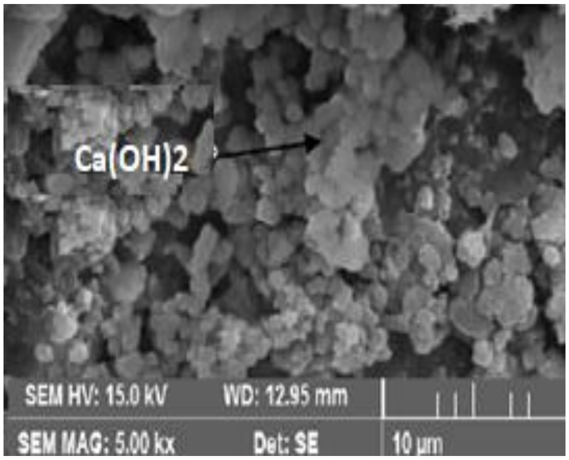
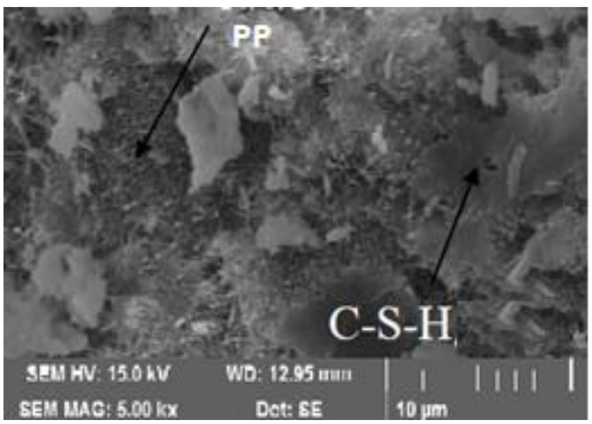


Fig 17. Shrinkage curve of the mortars.

Fibers not only have a direct physical effect on improving the mechanical behavior of mortars but also exert an indirect chemical effect on the progress of cement hydration. The SEM imaging and analysis were used to measure the microscopic composition of repair mortars and the effect of polypropylene fibers on their chemical properties. Fig. 18 illustrates the SEM of the repair mortar without fibers.



a) Without fiber.



b) With fiber.

Fig 18. Effect of fibers on the hydration process.

As shown in Fig. 18a, the C-S-H gel was organized from the hydration of C2S and C3S, but there were void regions in the repair mortar, which could decrease its strength. According to Fig. 18b, with the increase of fibers to the repair mortar, the action of hydration and formation of C-S-H gel, along with fibers, was carried out well and consequenced in better homogeneity of the repair mortar admixture. In other words, the increase of the fibers resulted in better adhesion of the repair mortar. The effect of fibers in improving the hydration process reduced the shrinkage of cement inside the mortar, and therefore, the shrinkage of the mortars reinforced with polypropylene fibers was less than that of the ordinary ones without fibers.

XRD device or X-Ray Diffraction device is one of the unique equipments for analyzing and determining the characteristics of crystals in the laboratory. The design principles of the XRD device are based on X-ray radiation to the sample at different angles and analysis of its diffraction or reflection pattern. The X-ray diffraction pattern for each material is unique. So far, the diffraction pattern of a large number of crystalline materials has been collected by XRD equipment.

The specimens were subjected to XRD tests for a more accurate evaluation of the phases and the crystallographic structure of the concrete particles before and after the addition of the PP fibers. The results are shown in Fig. 19. As can be seen, with the addition of the fibers, the peak of $Ca(OH)_2$ or calcium hydroxide, which is shown with a black arrow, was reduced. Considering that the hydration reaction products are equal to hydrated calcium silicate and calcium hydroxide, therefore, with the decrease of calcium hydroxide, it is concluded that the amount of hydrated calcium silicate (C-S-H gel) has increased.

In other words, the calcium silicate hydrate gel increased with the consumption of the calcium hydroxide. The conversion of the calcium hydroxide in the mortar structure into the calcium silicate hydrate during the hydration process can affect the mortar's ultimate properties and improve the mortar strength.

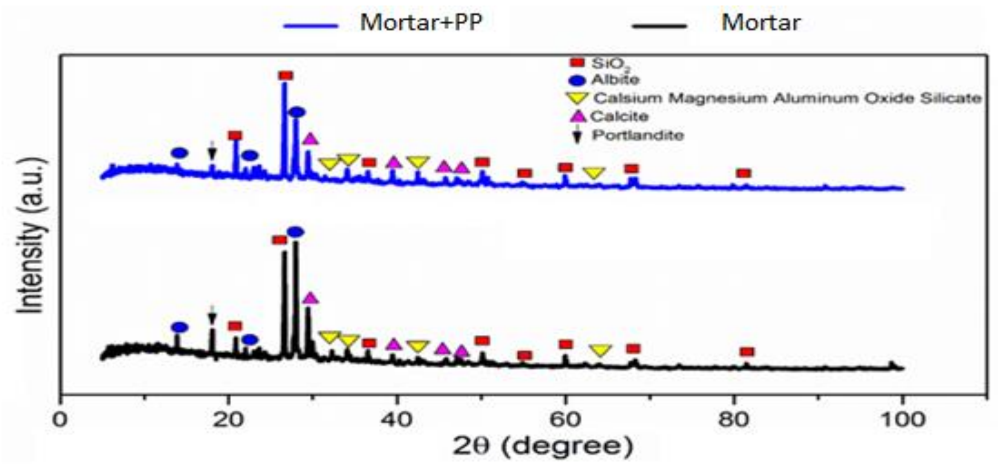


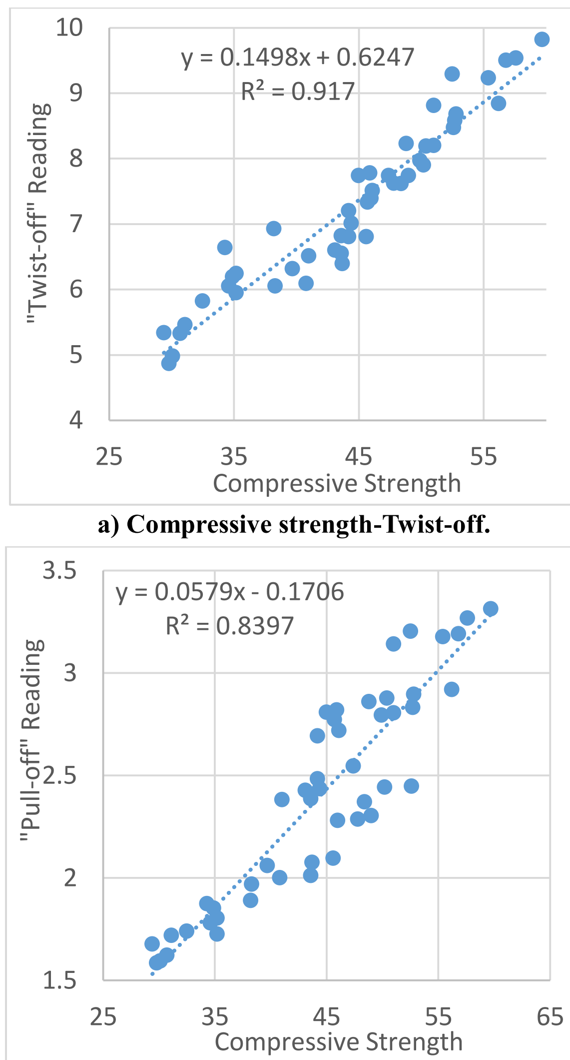
Fig 19. The X-Ray Diffraction pattern for the fiber-reinforced mortar.

3.5. Evaluation of Compressive Strength

This section provides the correlation among the "pull-off" and "twist-off" results and the compressive strength of fiber-reinforced repair mortars. Fig. 20 plots the compressive strength versus the in-situ test results for the polypropylene fiber-reinforced mortars.

According to Fig. 20a, the coefficient of determination and correlation among the "twist-off" results and the compressive strength of the fiber-reinforced repair mortars were found to be 0.91 and 0.95, respectively, by linear regression. Thus, the twist-off results could be used to evaluate the compressive strength of the polypropylene fiber-reinforced mortars by the linear calibration curve in Fig. 20a and the equation y=0.15x+0.62 at a confidence level of 95%.

As can be seen in Fig. 20b, the coefficient of determination and correlation among the "pull-off" results and the compressive strength of the fiber-reinforced repair mortars were found to be 0.925 and 0.961, respectively.



b) Compressive strength-Pull-off.

Fig 20. Correlation among the in-situ test results and compressive strength of fiber-reinforced mortars (MPa).

Therefore, the pull-off results can be utilized to obtain the compressive strength of the polypropylene fiber-reinforced mortars by the linear calibration curve in Fig. 20b and the equation y=0.06x-0.17 at a confidence level of 96%. standard deviation is equal to 3.7%.

3.6. Effects of Fibers on the Compressive Strength of Mortars

Certain content of fibers increases the ability of materials to resist stresses by delaying cracking and transferring the stresses across the crack propagation direction. This enables the mortar to resist much larger deformations under stress peaks. Fig. 21 compares the compressive behavior of non-reinforced and propylene fiber-reinforced mortars.

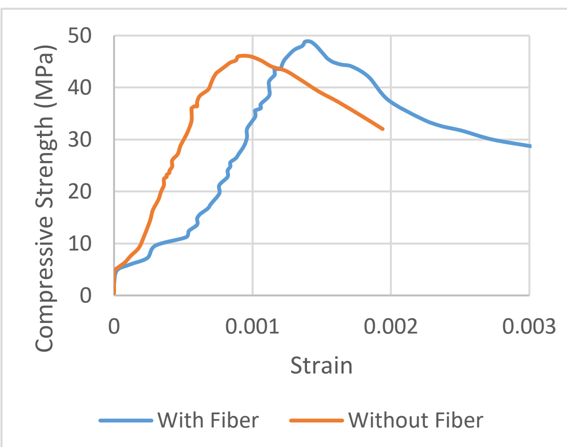


Fig 21. Compressive behavior comparison of non-reinforced and reinforced mortars.

According to Fig. 21, fibers increased the compressive strength of the repair mortars. The ultimate strength of the non-reinforced mortar was found to be 46 MPa at a strain of 0.00098, while that of the fiber-reinforced mortar was calculated to be 48.8 MPa at a strain of 0.0142. As can be seen, the maximum resistible deformation of the non-reinforced mortar was nearly 45% lower than that of the fiber-reinforced mortar.

Table 5 shows the compressive strengths of the repair mortars. According to Table 4, the addition of fibers at a volume fraction of 0.003 improved the compressive strength of the repair mortars at different ages. The addition of polypropylene fibers enhanced the compressive strength of the mortars by 4.8% on average.

Table 5. Compressive strengths of cement mortars (in MPa).

Mortar	7 Days	42 Days	90 Days
Non-reinforced	34.1	51.2	54.4
Fiber reinforced	35.8	53.1	56.6

4. Conclusion

The present study aimed to investigate the effect of polypropylene fibers and pre-stresses on the adhesion between mortar and concrete using "twist-off" and "pull-off" semi-destructive tests. The effect of fibers and pre-stress on the adhesion between the two layers was examined using scanning electron microscope images and X-ray diffraction. Furthermore, the aforementioned semi-destructive methods were employed to investigate the in-situ compressive strength of mortars at different ages. The result is equal to:

- Adding 0.3% of polypropylene fibers to the mortars reduced the shrinkage of the mortars by 11%.

- Adding Polypropylene fibers enhanced the shear and tensile bond strength by 76.8% and 41.7%, respectively.

- Considering the high correlation between the twist-off and pull-off results, affordable and available "twist-off" machines can be utilized instead of import and expensive "pull-off" machines for measuring concrete-mortar adhesion.

- An initial stress of 0.5 kg/cm^2 increased the shear and tensile adhesion at the age of 90 days by 12.8% and 13.3%, respectively.

- An initial stress of 0.1 kg/cm^2 increased the shear and tensile adhesion at the age of 90 days by 5% and 4.8%, respectively.

- The XRD results demonstrated that the addition of fibers to the mortars decreased $Ca(OH)_2$ and, consequently, increased C-S-H, which positively affected mortar properties.

- The SEM results revealed that hydration and C-S-H gel formation near fibers properly occurred and provided higher mortar uniformity.

- The twist-off and pull-off results can be translated into the compressive strength of propylene fiber-reinforced mortars by using the equations y=0.15x+0.62 and y=0.06x-0.17, respectively.

Conflict of interest:

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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