EFFECTS OF INITIAL PRESSURE AND FIBER ON BOND STRENGTH BETWEEN MORTAR AND CONCRETE SUBSTRATE USING TWIST-OFF AND PULL-OFF METHODS

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Curing and compaction are two major factors in the interface bond strength of concrete and repair mortars. Ignoring these two factors would create fine holes in the concrete-mortar interface and reduce the adhesion. Hence, the present study has aimed to evaluate the effects of initial pressure and fiber on adhesion between mortars and concrete substrates using the twist-off and pull-off tests. The effects of fibers on the shrinkage of mortars are also discussed. The influences of pre-pressure and fibers on the adhesion of the two layers were demonstrated using the scanning electron microscopy (SEM) and X-ray diffraction (XRD) methods. The results indicated that initial pressure had positive impacts on the interface shear and tensile bond strength in the twist-off and pull-off tests, and the effect of pre-pressure was greater on mortars with more aggregates. Moreover, fibers reduced the mortar shrinkage and increased the adhesion. Considering the high correlation between the twist-off and pull-off results, affordable and available twist-off apparatus can be employed instead of expensive pull-off apparatus to measure the concrete-mortar adhesion.

Keywords: *"Twist-off", "Pull-off", Pre-pressure, Bond, Fiber..*

1. Introduction

The suitable compaction of a repair mortar applied to the concrete substrate is a factor that enhances the adhesion between the mortar and concrete. The mortar-concrete interface is of great importance since unsuitable compaction would create fine holes in the interface and contribute to the reduction of the bond strength. There are numerous methods to increase the bond strength between mortar and concrete. Extensive research studies have been conducted in this field. Some of these techniques are to prevent the reduction of bond strength, reduce the amount of shrinkage, or use fibers in the mortar.

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 [1]. Glass fiber-reinforced polymers are another material that can be employed in, for example, the strengthening of columns in reinforced-concrete structures [2]. Steel-reinforced grout (SRG) is a new repair material that improves concrete surface adhesion [3].

The shrinkage during the setting of mortar is due to the loss of moisture inside the mortar. Considering that the hydrated cement paste has capillary pores containing some water, the shrinkage occurs after removal of this moisture from the pores [4]. Based on the conducted studies, the growth of early fractures in multi-layer concrete systems is mainly related to the absence of adequate compatibility between the repair layers characteristics and substrate concrete [5]. One of these features is the drying shrinkage. According to reports of some researchers, the difference between the values of shrinkage occurred at the joint of the repair layer and existed concrete, is the main cause of adhesion loss between the two systems [6]. Although the cementitious mixtures tend to be shrinkage [7], so the early setting of concrete causes the shrinkage of material and formation of very small cracks on the concrete surface [8]. For concrete members confined by nearby members, cracks may also occur due to stresses arising from the excessive shrinkage [9].

Fibers improve the behavior of concrete under compressive stresses [10, 11] and have a positive effect on the stress-strain curve [12]. A research study conducted on this found that adding polypropylene fibers reduced dry shrinkage of the specimens [13]. Shakir et al. [14] 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. [15] 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. [16] 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

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excessive volume fraction of fibers negatively impacts the properties of cement materials [17-19]. Given that suitable compaction of a repair mortar applied to a concrete substrate enhances the adhesion between the mortar and concrete, this study evaluated the effects of initial pressure on the adhesion between the fiber-reinforced repair mortars and the concrete substrate using the twist-off [20] and pull-off [21] tests. The effects of fibers on the shear and tensile bond strength of the mortars were also explored in in-situ methods and at different curing ages. In a study on the effect 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% [22]. In another study evaluating the strength of different compacted concretes, it was concluded that the compressive strength results of the “Schmidt hammer” and “Ultrasonic pulse velocity” tests are highly influenced by the method of compaction and compaction [23]. Also, in another study on the effect of compression on the compressive strength of ordinary concretes, it was found that the resistance of concrete mechanically compacted may be between 4-8 MPa higher than the one of the same concrete manually compacted [24].

Results indicated the positive effect of pre-pressure on shear and tensile bond strength between the mortar and concrete substrate. Furthermore, fibers reduced the mortar shrinkage and increased the adhesion. There was also a high correlation between the twist-off and pull-off methods. Therefore, a simple and inexpensive twist-off device can be utilized instead of a pull-off device to measure the shear and tensile bond strength between the mortar and concrete.

2. Material and methods

2.1. Materials and Making the Samples

Type II cement, with a density of 3007 kg/m^3. The densities of saturated surface dry gravel and sand are 2330 and 2510 kg/m^3, respectively, and their maximum sizes are 19 and 4.75 mm, respectively. Water absorption of sand is listed as 2.6 and 3.2% according to ASTM C128 [25] and ASTM C127 [26]. The polypropylene fibers were used with 0.3% mortar volume.

To measure the adhesion between the fiber-reinforced mortar and concrete substrate, first, cubic concrete samples with dimensions of 150 mm were prepared as a substrate (Fig 1a) And were fully submerged in water for a period of 60 days. In the next step, they were taken out of the water after the mentioned period of time, and a concrete saw was utilized to ensure a smooth surface featuring adequate strength (Fig 1b). By providing a surface showing sufficient resistance, mechanical locking and clamping interference in the mortar/concrete joint surface was reduced to a minimum. Next, the substrate concretes were put within molds, and the surface of the base concrete was fully saturated without having water droplets on the concrete surface, and thick cement water slurry was applied over the mentioned surface prior to the applying the repair mortar (Fig 1c) and before this slurry had solidified, 25mm thick mortars were applied to the concrete substrate.

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 specimens were kept in the water for seven days and then released until the test time. The tests were carried out at the ages of 7, 42, and 90 days. The repairing mortars have a ratio of 0.5 for water/cement. The ratio of cement/sand in one mortar is 1/2 (M1), and in the other is 1/3 (M2). In the laboratory, 25 and 100 kg weights were placed manually on the mortars according to Fig 2, and 1100 and 2250 kg weights were applied using a concrete breaker jack. We ensured that all the applied pressures were transferred to the mortar, bearing in mind the fact that the substrate concrete and the repair mortar are within a metal mold and bound from all sides, and also using nylon to prevent the mortar from leaking.

2.2. Experimental methods

To measure the tensile bond strength by using the pull-off method, a core with a diameter of 5 cm is drilled into the concrete (Fig 3a). Then, a steel cylinder with a diameter of 5 cm is attached and pulled by a machine until it fractures, as shown in Fig 3b. To measure the shear bond strength between repair layers and concrete surfaces by

a) Substarte Concrete b) Cutting the substrate with saw c) Applying Grout over the substrate

Fig. 1 - Stages of producing the samples required to measure the existing mortar-concrete adhesion

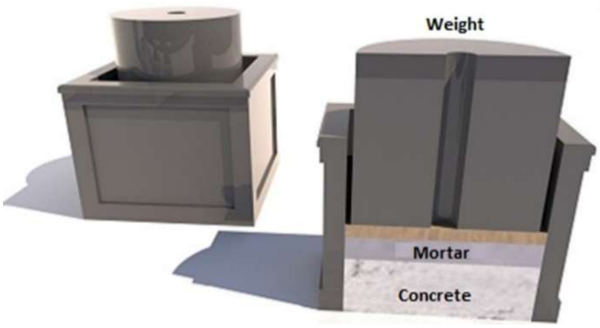
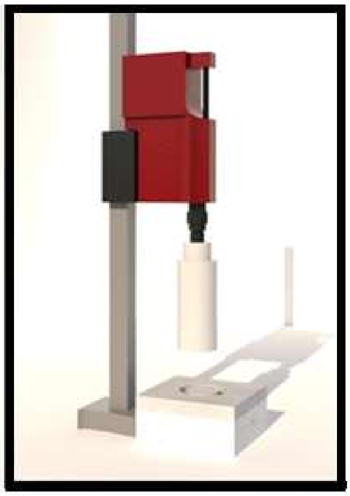


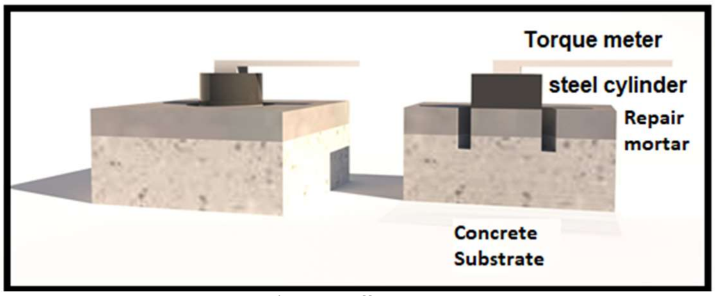
Fig. 2 - Applying Pressure to the Mortars



a) Core drilled

b) Pull-off method

c) Core fracture



d) Twist-off method

Fig. 3 - Tensile and Shear bond strength

using the twist-off method, it is required to drill a core on the repair surface at a depth of nearly 5 cm into the concrete substrate. 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 3c,d).

Based on the ultimate torsional moment, the adhesion of the repair layer is calculated using the relation between the shear stress τ and torsional moment T as Eq. (2). The shrinkage of the specimens was calculated according to the ASTM C157 [27] and ASTM C490 [28] Standards. The prismatic shrinkage molds had a cross-section of 25*25 mm and a height of 285 mm.

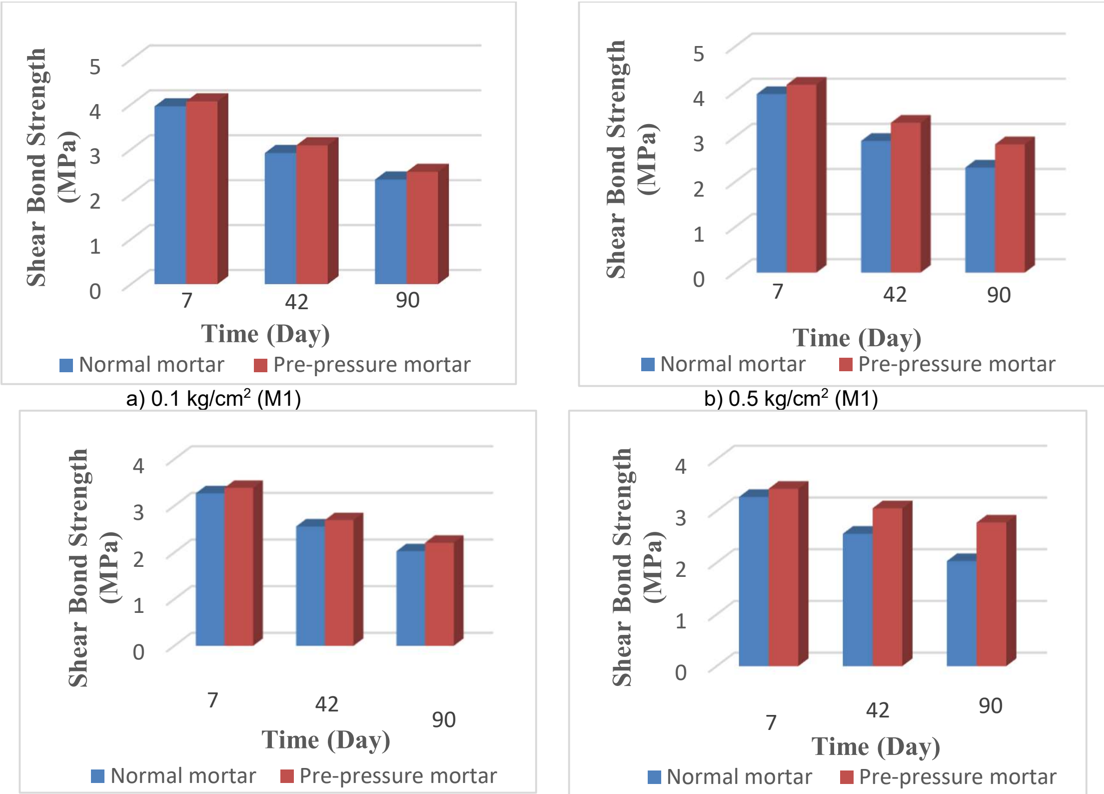
$$\tau = \frac{Tc}{J} \qquad (2)$$

To evaluate the compressive strength, a quantity of 150 mm cubic samples was made, placed into water. The samples were then extracted and tested using the twist-off and pull-off tests at the ages of 7, 42 and 90 days.

3. Results and Analysis

3.1. The effect of pre-pressure on the shear bond strength

Figure 4 shows the twist-off test results to obtain the shear bond strength for M1 and M2 mortars under various pre-pressure. Figure 4.a shows that 0.1 kg/cm^2 of pre-pressure on the M1 mortar has increased the shear bond strength. However, the increase in shear bond strength is not significant. applying 0.1 kg/cm^2 increases the shear bond strength at the ages of 7, 42, and 90 days by



a) 0.1 kg/cm^2 (M1)　b) 0.5 kg/cm^2 (M1)

c) 0.1 kg/cm^2 (M2)　d) 0.5 kg/cm^2 (M2)

Fig. 4 - Results of the twist-off test for mortars under various pre-pressure

2.8, 5.8, and 7.2%, respectively. But figure 4.b shows that applying 0.5 kg/cm^2 increases the shear bond strength of M1 mortar at the ages of 7, 42, and 90 days by 5, 13.7, and 21.9%, respectively.
Figure 4.c shows that applying 0.1 kg/cm^2 increases the shear bond strength of M2 mortar at the ages of 7, 42, and 90 days by 3.7, 5.4, and 8.8%, respectively. Figure 4.d shows that applying 0.5 kg/cm^2 increases the shear bond strength of M2 mortar at the ages of 7, 42, and 90 days by 4.9, 19.1, and 36.9%, respectively.

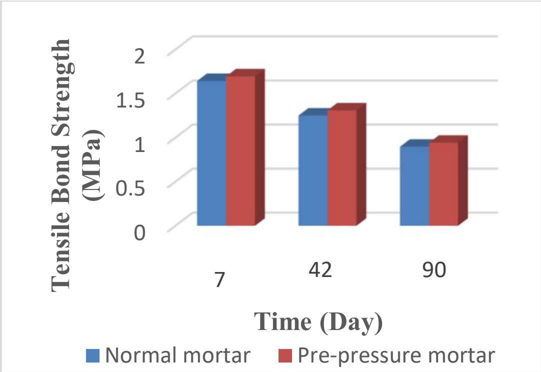
3.2. The effect of pre-pressure on the tensile bond strength

Figure 5 shows the pull-off test results to obtain the tensile bond strength for M1 and M2 mortars under various pre-compress. Figure 5.a shows that applying 0.1 kg/cm^2 increases the tensile bond strength of M1 mortar at the ages of 7, 42, and 90 days by 3.6, 4.8, and 5.6%, respectively. But figure 5.b shows that applying 0.5 kg/cm^2 increases the tensile bond strength of M1 mortar at the ages of 7, 42, and 90 days by 4.9, 9.6, and 16.9%, respectively.

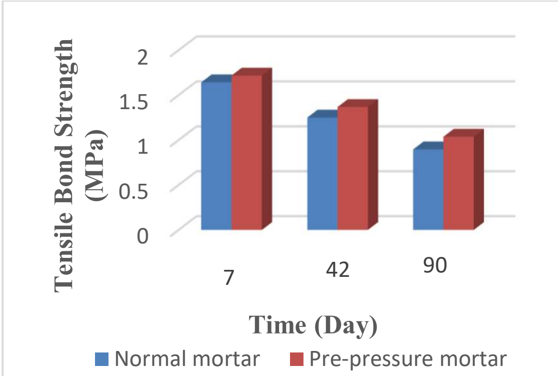
Figure 5.c shows that applying 0.1 kg/cm^2 increases the tensile bond strength of M2 mortar at the ages of 7, 42, and 90 days by 4.5, 6.3, and 7.5%, respectively. But figure 5.d shows that applying 0.5 kg/cm^2 increases the tensile bond strength of M2 mortar at the ages of 7, 42, and 90 days by 6.7, 11.2, and 30.1%, respectively.

In general, it is considered that at a pressure of 0.1 kg/cm^2, the amount of increase is not significant, but at a pressure of 0.5 kg/cm^2, the amount of increase in bond strength is greater, especially at older ages, this increase is more noticeable. Also, by comparing the two types of mortar with each other, it is observed that the mortar M2 is more affected by pre-pressure. The reason for the increase in bond strength between mortar and concrete can be due to the higher compact of mortar under pressure because one of the important factors on the amount of adhesion is the compaction of the repair layer. For this reason, for mortars containing more aggregate (M2), the pressure on the mortar has a greater effect on the bond strength. Also, by applying pre-pressure, the possibility of contact of mortar particles with the concrete surface of the substrate increases and this increases the bond strength. No high effect on adhesion was observed at high pressures (5 and 10 kg/cm^2) and therefore the results were not mentioned. Of course, one of the reasons was due to the release of grout into the mortar during the application of pressure. As shown in figures 4 to 5, the adhesion strength between the mortar and the concrete decreased over time. As the repair layer shrinkage is one the effective factors on adhesion, these layers cracked and it lowered the adhesion strength between the layer and the concrete substrate. In this study, this occurred, but the fibers could be used to lower the drying shrinkage in repair mortars which is discussed in later sections of this paper.

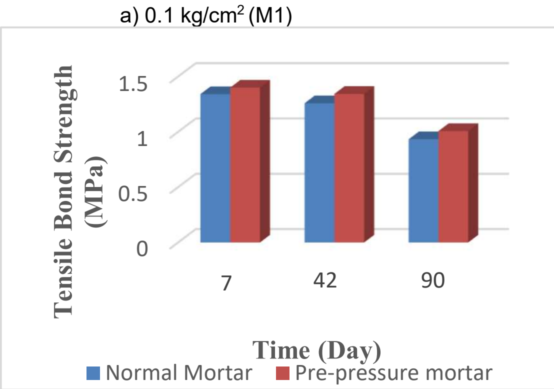
There is a lot of research found on the adhesion between different repair layers and the



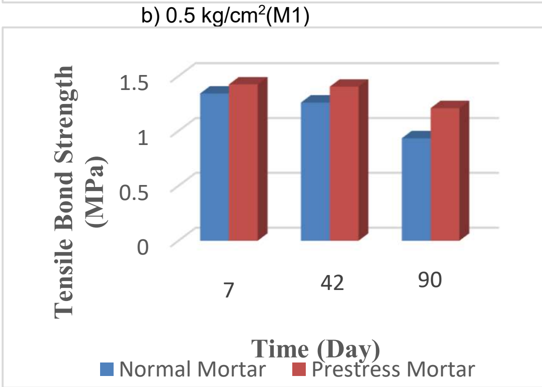
a) 0.1 kg/cm^2 (M1)



b) 0.5 kg/cm^2(M1)



c) 0.1 kg/cm^2 (M2)



d) 0.5 kg/cm^2(M2)

Fig. 5 - Results of the pull-off test under various pre-pressure

impact of shrinkage on adhesion. In a study using the "friction-transfer" test about the effect of shrinkage on the adhesion between mortars modified by polymer and the concrete substrate, it was found that 15% SBR polymer addition to the mortar could decrease the shrinkage by 36.1% and also increase its adhesion by 269.9% [30]. In another study on reducing the adhesion strength between repair mortar and the concrete substrate over time, it was found that the failure of curing the samples could dramatically lower the adhesion strength so that the layer cracked due to shrinkage increase after 90 days and the adhesion strength was lowered by zero [31]. In another research, a nearly 59 percent increase found in the shrinkage of the repair mortars because of the failure of curing. As this shrinkage could increase the shear stresses in the interface of the mortar and the concrete substrate, a 3.5 times reduction was found in the adhesion of the samples [32].

One of the most dominant bond strength theories is the theory of physical absorption. This theory plays a significant role in the bond strength between 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

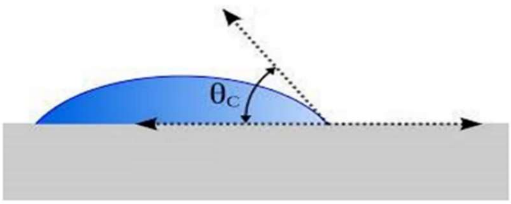


Figure 6. Liquid and solid contact angles [29]

in this case) is determined by the contact angle criterion [29]. This criterion has been indicated in Figure 6.

As observed, applying pre-compress on the repair mortar that has not yet hardened increases the bond strength between the mortar and the substrate surface. One of the reasons for this is due to higher density and greater contact surface of the mortar components with the substrate 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. Figure 7 indicates the areas related to 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 physical and mechanical properties of the composite. 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. Effect of Fiber on the Bond Strength

Figure 8 illustrates the bond strength between the pp fiber-reinforced mortar and concrete. As can be seen, fibers improved the bond strength. The addition of fibers increased the shear bond strength by 41% and 76.8% at the ages of 42 and 90 days, respectively. Also the addition of fibers increased the tensile bond strength by 23.8% and 41.7% at the ages of 42 and 90 days, respectively.

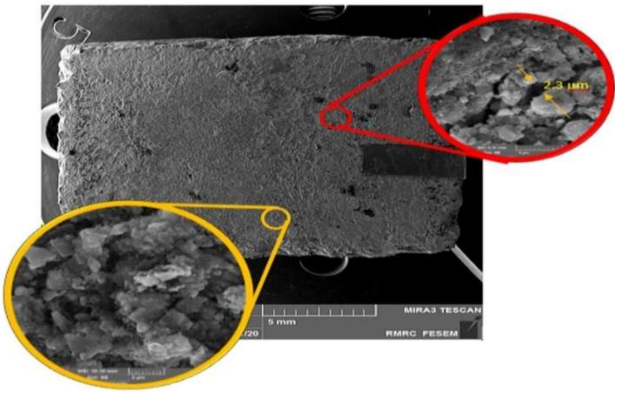
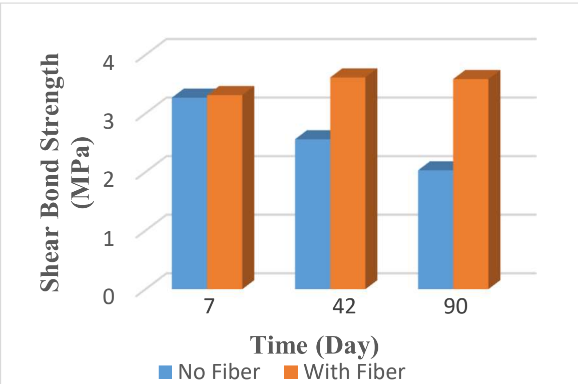


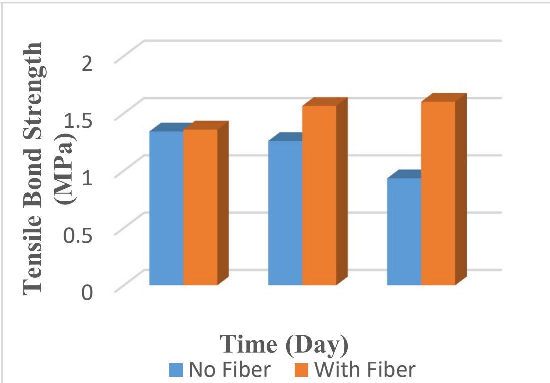
Fig. 7- Microscopic image of the surface of the mortar

cement hydration process completion that may significantly affects the mortar strength reduction. According to Figure 9b, 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. In other words, the addition of the polypropylene fibers resulted in better cohesion of the 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.

As seen before, the polypropylene fibers can indirectly and chemically improve the mortar strength, but their mechanical effects are most. A certain amount of fibers may increase the materials withstanding against the applied stresses. This happens because of cracking delay and transferring the applied stresses across the cracking path so that the mortar can withstand much larger displacements under peak stresses. The specimens were subjected to XRD tests for a more accurate evaluation of the phases and the crystallographic structure of the concrete particles



a) Shear bond strength



b) Tensile bond strength

Fig. 8 - Effect of Fiber on the Bond Strength

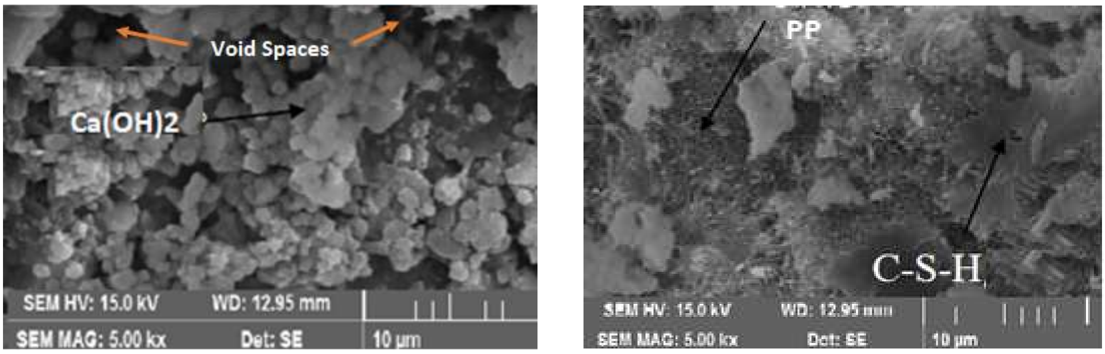
One of the main factors affecting adhesion is shrinkage. Result shows the addition of the fibers to the mortar reduced the 90-day shrinkage by 11.1%, on average.

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 evaluate the microscopic structure of mortars and the effect of polypropylene fibers on their chemical properties. Figure 9 illustrates the SEM image of the mortar with and without fibers.

As seen in fig 9a, the hydrated paste is forming in which separate big crystals in the multifaceted prism form represent calcium hydroxide or portlandite, but some voids are seen in the mortar which have a perfect form due to the before and after the addition of the PP fibers. The results are shown in Figure 10. 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. In other words, the calcium silicate hydrate (C-S-H) 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.

3.4. Comparing the results of the "twist-off" and "pull-off" methods

Figure 11 shows the relationship between shear bond strength obtained by the twist-off method and the tensile bond strength obtained by the pull-off method. Figure 11 shows that the



a) Without Fiber b) With Fiber

Fig. 9 - SEM images

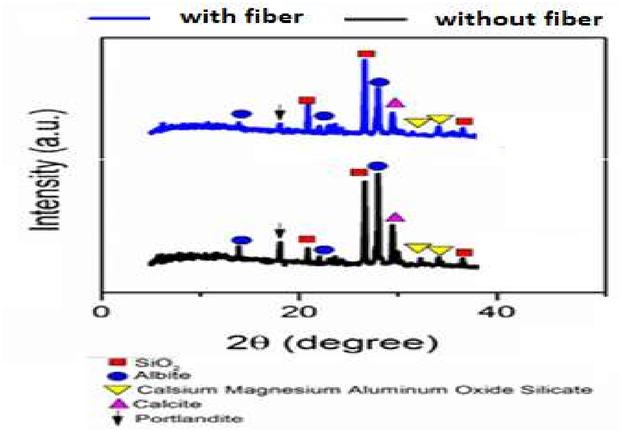


Fig. 10 - The X-Ray Diffraction pattern for the fiber-reinforced mortar

coefficient of determination between the results of the pull-off and twist-off methods is 0.96. Then it is possible to obtain the bond strength between the mortar and the concrete, by a cheap and easy twist-off machine instead of using an expensive pull-off machinery.

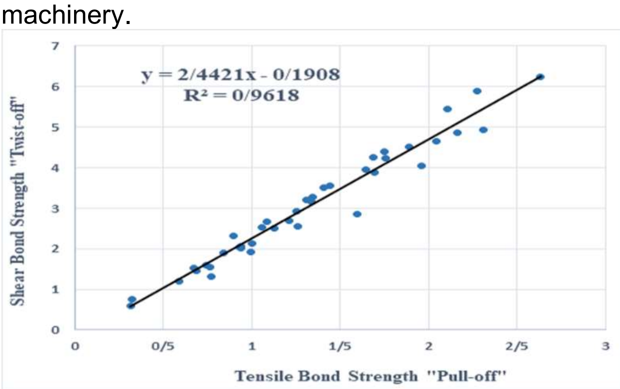


Fig. 11- Comparing the results of the twist-off and pull-off methods (MPa)

3.5. Evaluation of the compressive strength

Result shows adding fibers to repair mortars increased the compressive strength on average by 4.6%. Fibers were added to the mortar to increase the strength, delay cracking, and transfer stress along the crack width so that the mortar with fiber can withstand greater deformation under stress.

4. Conclusion

- Given the high correlation and determination coefficients between the results of the twist-off and pull-off tests for the experiments performed in this study, it is possible to obtain the adhesion between the mortar and the concrete, by a cheap twist-off machine instead of using an expensive pull-off machinery.

- Applying 0.5 kg/cm^2 of pressure has increased the shear and tensile bond between the repair mortar and concrete layers at the age of 90 days by 36.9% and 31.4%, respectively.

- Applying 0.1 kg/cm2 of pressure has increased the shear and tensile bond between the mortar and the concrete at the age of 90 days by 8.8% and 5.8%, respectively.

- Polypropylene fibers reduced drying shrinkage by 11% and enhanced the shear and tensile bond strength by 76.8% and 41.7%, respectively, in the twist-off and pull-off tests.

- 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 the mortar properties.

- The SEM results revealed that hydration and C-S-H gel formation occurred properly near fibers and provided higher mortar uniformity. (Needless to mention, further research and experiments are required before these findings can be stated with full certainty.)

- The compressive strength of the repair mortars has been improved by adding fibers. Adding fibers increased the compressive strength on average by 4.6%.

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