J. Appl. Comput. Mech., 8(2) (2022) 493-509
DOI: 10.22055/JACM.2020.32921.2101

ISSN: 2383-4536
jacm.scu.ac.ir

Shahid Chamran University of Ahvaz

Journal of Applied and Computational Mechanics

Research Paper

# Experimental and Finite Element Study to Determine the Mechanical Properties and Bond Between Repair Mortars and Concrete Substrates

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Received March 11 2020; Revised March 29 2020; Accepted for publication April 04 2020.
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**Abstract.** The separation between repair mortars and the concrete substrate is one of the serious problems in repairing concrete structures. One of the main causes of this separation is the lack of proper curing and, consequently, excessive shrinkage of the repair mortar, which reduces the bond strength between the concrete substrate and the repair layer and has an adverse effect on the compressive and tensile strength of the repair mortars. In this paper, the mechanical properties, shrinkage of repair mortars, as well as their shear and tensile bond strength is investigated on the concrete substrate of different ages under the curings of "abandoned in the laboratory space," "water-submerged" and "curing agent." In-situ "friction-transfer" and "pull-off" methods are used to measure adhesion. Furthermore, the relationships between compressive strength, tensile strength, and readings are obtained from "friction-transfer" and "pull-off" methods on repair mortars and the stress distribution method used in the above-mentioned methods are presented using nonlinear finite element analysis (Abaqus/CAE). The results indicate a significant effect of curing method on shrinkage and mechanical properties of repair mortars; as a result, effective curing increases the shear and tensile bond strength at the substrate and repair layer joint boundary. It is also observed that there is a linear relationship between the experimental results obtained from the two methods used in this study with a high correlation coefficient, highly consistent with the results obtained from nonlinear finite element analysis. Thus, they can be used as in-situ methods for determining the compressive and tensile strength of repair mortars.

**Keywords:** Curing, Mechanical Properties, Friction-Transfer, Pull-Off, Repair Mortar, Shrinkage

## 1. Introduction

Since a chemical reaction called hydration is carried out after mixing Portland cement with water, the rate of development of this reaction affects the mechanical properties and the bond strength of the mortar. Although the amount of freshly mixed mortar water is usually excessively needed for cement hydration to obtain sufficient fluidity, hydration is delayed or not sufficiently carried out, due to high water loss as a result of evaporation. In the first few days after the mortar is made, hydration is relatively quick if the temperature and humidity are optimal; however, the retention of water inside the mortar is important during this time and should prevent or significantly reduce water evaporation. According to research, early failures in multilayer concrete systems are mainly due to insufficient compatibility between the characteristics of repair layers and substrate concrete [1]. One of these features is drying shrinkage. According to some researchers, the main cause for the collapse of the adhesion between the two systems is the difference in the amount of shrinkage between the repair layer and the old concrete [2]. As cement mixtures tend to shrink [3], early drying of concrete causes shrinkage and fine cracks on the concrete surface [4]. Cracks may also occur for concrete members restricted by adjacent members due to excessive shrinkage [5]. Shrinkage has a variety of causes and is mainly caused by the outflow of water from the cement paste. One of the important shrinkages is the shrinkage caused by drying (drying shrinkage). Increased water-cement ratio, decreased ratio of concrete volume to its surface, and increased cement-aggregate ratio are some of the factors affecting the increase in shrinkage. The failure of joint surfaces between repair layers and the substrate is often due to differences in shrinkage between them [6]. Excessive mortar shrinkage can be prevented by proper curing and moisture retention, resulting in greater bond strength between the repair mortar and the concrete substrate. In a study on the effect of repair layer shrinkage on adhesion, it has been reported that moisture retention inside the repair layer lasts for one week to reduce shrinkage and optimal curing mode [7]. Other influencing factors include the compressive strength of the repair mortar and the surface of the substrate layer on the adhesion between the repair mortar and the concrete substrate. The compressive strength of the repair layer is directly related to the adhesion between the repair layer and the concrete substrate such that an increase in compressive strength of the repair mortar from 70 to 114 MPa has resulted in

Published online: July 29 2020

an increase in bond strength from 7.2 to 18 MPa [8]. In addition, the substrate surface has a major impact on the adhesion between the repair layer and the concrete substrate. However, if the substrate surface is exposed to sand, the adhesion between the concrete substrate and the repair layer can increase up to 14.5% [9].

Various methods can be used to measure the adhesion of joint surfaces between the concrete substrate and the repair layer. The evaluation of bond strength between layers can be in the form of tensile stresses, shear stresses, and a combination of compressive and shear stresses, depending on the stress state of the specimens. Ohama et al. (1986) used a composite beam in which half of the specimen was made with the substrate concrete and the other half with the repair mortar (Figure 1a). In this test, a centralized force is applied in the middle of the aperture [10]. Chen et al. (1995) used the double shear plate according to Figure 1b [11]. Abbottier et al. (1996) proposed a bending test according to Figure 1c where the repair mortar is placed between the two concrete halves and the specimen is tested by applying two centralized loads at one-quarter of the aperture [12]. Kunieda et al. (2000) used a symmetrical specimen with a slit in the middle of the aperture equal to one-third the height of the cross-section from below as shown in Figure 1d. Half of the specimen is concrete, and the other half is the repair mortar. In this test, two centralized loads were used at one-fifth of the aperture [13]. Carnio et al. (1953) proposed the splitting test (Figure 1f). In this test, the adhesion between surfaces is determined by applying two opposing compressive forces parallel to the joint surface [14]. In ASTM C1583 [15], the "pull-off" test is introduced. In this method, the tensile force is applied to the partial core through the tensile device (machine) to bring about failure (Figure 1f). Craig (1976) proposed a slant shear test (Figure 1g) where the joint surface is subjected to a combination of compressive and shear stress [16]. Notwithstanding, Naderi (2012) [17] has considered the results of compressive and shear stress tests unreliable both theoretically and practically.

This study used the "friction-transfer" method as well as the "pull-off" method to determine the bond strength between the repair mortar and the concrete substrate [18]. In the "friction-transfer" method, a partial core is first created by the coring machine. Then, the metal device is fixed to the partial core and a torsional moment is inserted through a conventional torque meter to bring about failure. In addition to measuring the bond between the repair layers and the concrete substrate and the effect of shrinkage on it, the relationships between compressive strength, tensile strength, and readings obtained by "friction-transfer" and "pull-off" methods on repair mortars and stress distribution methods in the above in-situ methods are also presented using nonlinear finite element analysis (Abaqus/CAE).

## 2. Laboratory Work

### 2.1. Consumables

The type of cement used is type II with a density of 3007 kg/m$^3$. Table 1 shows the chemical properties of Type II cement. The aggregates were used with a maximum size of 19 and 4.75 mm, respectively; their grading was conducted according to ASTM C136 [19]. The water absorption rate of aggregates was 2.6% and 3.2% according to ASTM C128 [20] and ASTM C127 [21] standards, respectively. The saturated aggregate density of the dry surface is 2330 and 2510 kg/m$^3$, respectively. Figure 2 shows the aggregate grading diagram.
The two-component adhesive used is made of epoxy resin with a "one-by-one" volume composition and a polyolefin curing agents. Table 2 shows the mechanical properties of an epoxy resin adhesive.

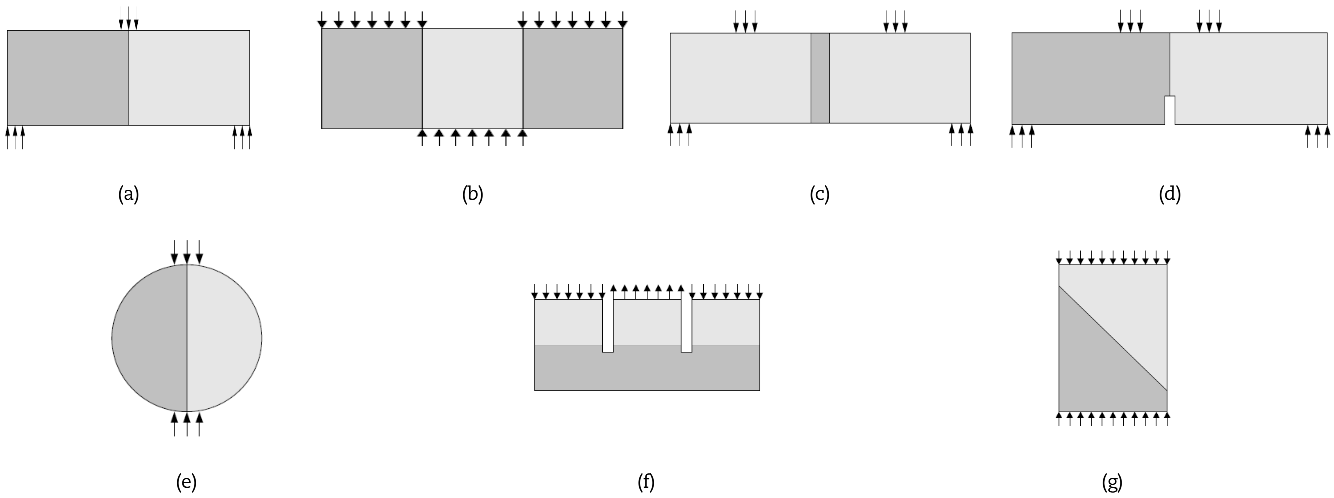



**Fig. 1.** Different methods for determining adhesion between the repair layer and the concrete substrate

**Table 1.** Chemical Properties of Type II Cement

| Chemical Properties | $Fe_2O_3$ | $SiO_2$ | $Al_2O_3$ | CaO | $Na_2O$ | $K_2O$ | $SO_3$ | MgO | LOI | $C_3A$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Weight (%) | 3.84 | 21.05 | 4.81 | 62.44 | 0.74 | 0.26 | 1.99 | 3.20 | 1.89 | 6.25 |

**Table 2.** Mechanical Properties of a Two-component Epoxy Resin Adhesive

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

**Table 3.** Substrate Concrete Weight Ratios (kg/m$^3$)

| Cement | Gravel | Sand | Water | W/C Ratio | Superplasticizer |
|---|---|---|---|---|---|
| 534 | 664 | 835 | 187 | 0.35 | 2.61 |

**Table 4.** Properties of the superplasticizer used in building the substrate concrete

| Type of Material | Color | Specific Gravity | PH Value |
|---|---|---|---|
| Polycarboxylate | Light Brown | 1.11 kg/l | 5 |

**Table 5.** Specifications of the Mortar Made

| Short Name | Cement-Sand Ratio | Water-Cement Ratio |
|---|---|---|
| M1 | 3 : 1 | 0.5 |
| M2 | 2 : 1 | 0.5 |

### 2.2. Substrate concrete

In this study, conventional Portland cement Type II was used to make the substrate concrete. The 28-day compressive strength of the cubic specimen of the concrete substrate is 57 MPa. Table 3 shows the mix design used to make the substrate concrete. First, the aggregates were exposed to the laboratory atmosphere for 72 hours due to the varied moisture content of the aggregates in the open space. Then, their water uptake until the saturation point with the dry surface was calculated and was added to the mixing water.
Table 4 shows the superplasticizer properties used in building the substrate concretes.

### 2.3. Repair Mortar

Two different cement-to-sand ratios, namely 1:3 and 1:2, have been used for building repair mortars applied to the concrete substrate. The water-to-cement ratio in both mortars is 0.5 (Table 5).

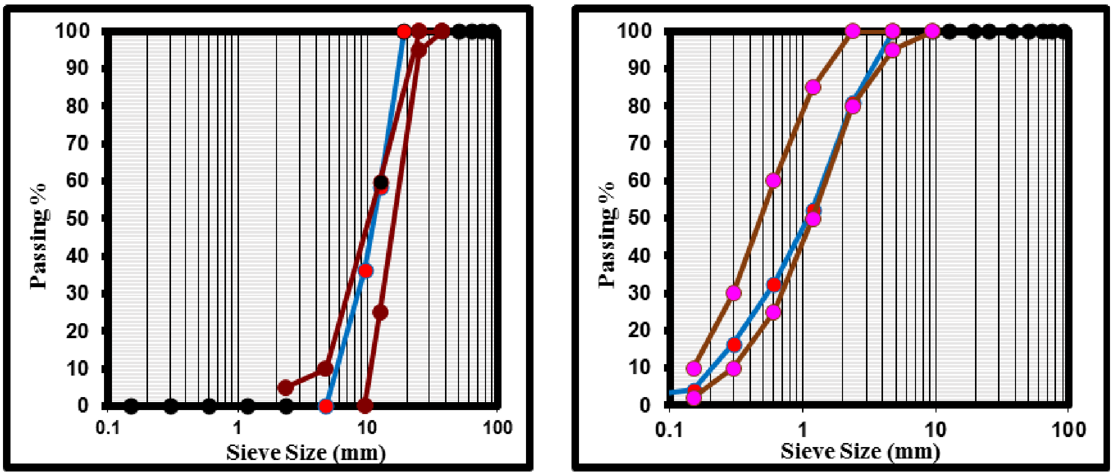
### 2.4. Specimen Preparation

At first, cubic concrete specimens with 150 mm dimensions were prepared as substrates and immersed in water for 60 days. Then, they came out of the water after that period. Concrete saws were used to have a smooth surface with sufficient strength to minimize the interference between mechanical interlocking at the mortar-concrete interface by providing the surface with sufficient strength. The concrete substrate surface was completely saturated before applying the repair mortar and the rigid cement slurry (grout) was applied to the surface without any water droplets on the concrete surface. Then, repair mortars were applied to the concrete substrate before the drying of slurry. The specimens were made to determine compressive strength, tensile strength, and shrinkage of repair mortars simultaneously with applying repair layers and removed from the mold after 24 h and subjected to "water-submerged", "curing agent" and "abandoned in the laboratory spaced" curing. Afterward, they were excised from curing at 7, 42, and 90 days of age and were subjected to the required tests. Some of the specimens were kept in curing until the test time and some were cured for 7 days and then excised from curing. Furthermore, a number of specimens were initially abandoned in open space.

### 2.5. Laboratory Methods

#### 2.5.1. Friction-Transfer Method

To measure the shear bond strength between repair layers and concrete surfaces using the "friction-transfer" method, a partial core must initially be created at the repair layer surface so that the partial core depth extends approximately 5 mm into the concrete substrate. The 5mm penetration of the partial core into the concrete substrate is due to the possibility of partial core failure at the boundary between the substrate concrete and the repair layer and the strength of the concrete substrate and the repair layer can be evaluated by considering the bond strength of the repair layer. It should be noted that the repair layer, the concrete substrate, and the boundary between the two are simultaneously affected by the torsional moment with the continuation of the partial core depth into the concrete substrate during the test when the torsional moment is exerted.



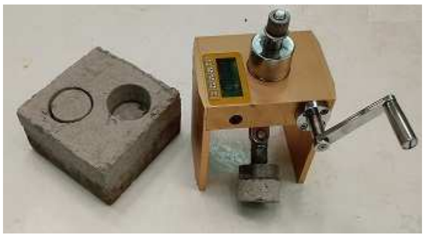

(a) Coarse-Grained (b) Fine-Grained

**Fig. 2.** Aggregate Grading Diagram

a) Determination of shear bond strength

b) Determination of mechanical properties repair mortar

**Fig. 3.** Performing the "friction-transfer" test



a) Determination of tensile bond strength

b) Determination of repair mortar mechanical properties

**Fig. 4.** Performing the "pull-off" test

In that case, the failure will occur at a level that is weaker than other parts. After the partial core is embedded, the metal "friction transfer" device is placed on the aforementioned partial core and fixed on the partial core using the side screws of the device. Then, the torsional moment is applied to the metal friction-to-partial core transmitter by applying a conventional manual torsiometer so that the partial core fails (Figure 3a). According to the final torsional moment (failure) and by using the equation between shear stress and torsional moment (Equation 1), the shear strength of the repair layer adhesion against the concrete substrate ( $\tau$ ) is calculated.

$$\tau = \frac{Tr}{J} \tag{1}$$

where *r* is the radius of the partial core and *J* is the second polar moment of the surface.

Due to the damage caused by the friction-transfer test, which is very minor, this test falls into the category of "partial failure" tests. The amount of damage caused by this test is up to 6 cm in diameter and up to 5 mm in depth to the thickness of the repair layer + 5 mm. In addition, to determine the relationship between the results of the "friction-transfer" test and the compressive and tensile strength of the repair mortars, a 25mm high partial core is first created in the repair mortar using a coring machine. Then, the "friction-transfer" device is fixed on it and a torsional moment is inserted into it by the torsiometer, thereby bringing about partial core failure (Figure 3b).

### 2.5.2. "Pull-Off" Method

In the "pull-off" test, to determine the tensile bond strength between the repair layer and the concrete substrate, a core with a 50mm diameter and a "repair layer + 5 mm" depth is first mounted on the test surface using a diamond drill bit and a metal cylinder with a diameter of 50 mm and a thickness of 20 mm is attached to the partial core. Then, the tensile force is applied to the cylinder by means of a "pull-off" device to make the partial core fail (Figure 4a). The tensile bond strength obtained at the contact surface between the repair layer and the substrate concrete ( $\sigma_T$ ) is obtained according to Equation 2. Furthermore, according to Figure 4b, the aforementioned metal cylinder is attached to the mortar surface and tensile force is applied to it without coring to determine the relationship between the results of the "pull-off" test and the compressive and tensile strength of repair mortars.

$$\sigma_T = \frac{P}{A} \tag{2}$$

where *P* is the tensile force and *A* is the contact area.

### 2.5.3. Measuring Drying Shrinkage

ASTM C157 [22] and ASTM C490 [23] standards were used to obtain the shrinkage rate of the specimens. Mortar shrinkage molds are like prisms with a square cross-section of 25 mm and a height of 285 mm. To determine changes in molded specimens, the length comparator shall be equipped with a dial gauge or any other calibrated measuring device for readings of 0.002 mm or less (Figure 5). According to the standard, at least 3 tests should be made for each specimen. Equation 3 is used to measure the amount of shrinkage in percent.

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

where *L* is the specimen length change, $L_x$ is the specimen reading minus the reference rod reading, *Li* is the initial specimen reading minus the reference rod reading, and *G* is the length of the reference rod.

a) Shrinkage measuring mold b) Reference rod and standard specimen c) Shrinkage comparator

**Fig. 5.** Equipment needed for shrinkage testing

a) Tensile Strength b) Compressive Strength

**Fig. 6.** Determination of the mechanical properties of the mortar

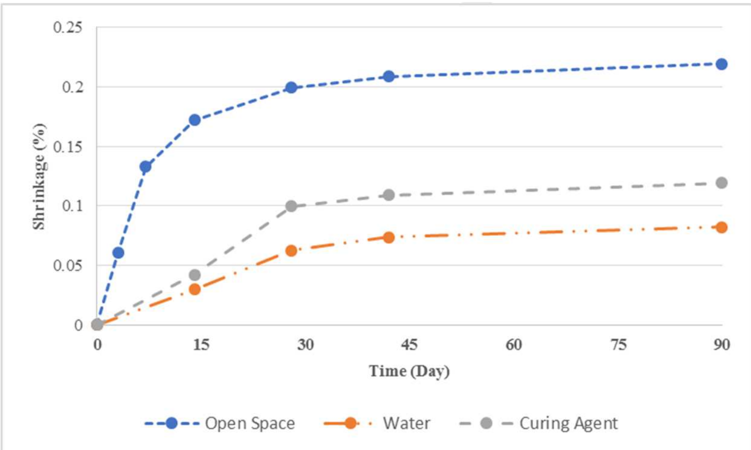



**Fig. 7.** Diagram of the M1 repair mortar shrinkage

### 2.5.4. Measurement of Mechanical Properties

The determination of the compressive strength of the mortar used was carried out using the ASTM C109 standard [24]. Six 50-mm cubic specimens were made for each mortar, their compressive strength was measured at different ages, and the mean results of these six specimens were considered as compressive strength (Figure 6a). The tensile strength of mortars was determined by making briquette specimens using the ASTM C190 standard [25] and an average of three specimens was considered for measuring tensile strength (Figure 6b).

## 3. Results and Analysis

### 3.1. Drying shrinkage

The results of determining the shrinkage of repair mortars as a result of drying are shown below. Each point on the following curves is the average of three readings. Figure 7 shows the diagram of M1 mortar shrinkage (0.5 : 1: 3) at different ages and under different curing operations for 7 days.

From Figure 7, it can be seen that the 90-day shrinkage value for M1 mortar cured as water-submerged, with curing agents and abandoned in open space are 0.0822, 0.1195, and 0.2196%, respectively. The amount of shrinkage for mortar abandoned in open space is 62% higher than that for mortars cured in water. Moreover, the amount of shrinkage in the open space increased by 45% compared to mortars cured with curing agents. At 42 days of age, the amount of the shrinkage of these mortars in the three curings above was 0.738, 0.1091, and 0.2088%, respectively. It is observed that the release of the specimen into the open space resulted in an increase in the shrinkage of 64 and 47% compared to the shrinkage of the specimen cured in water and with curing agents.

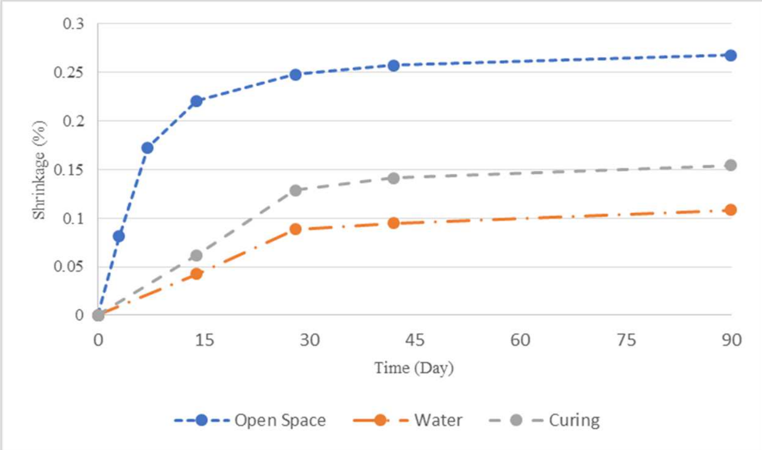
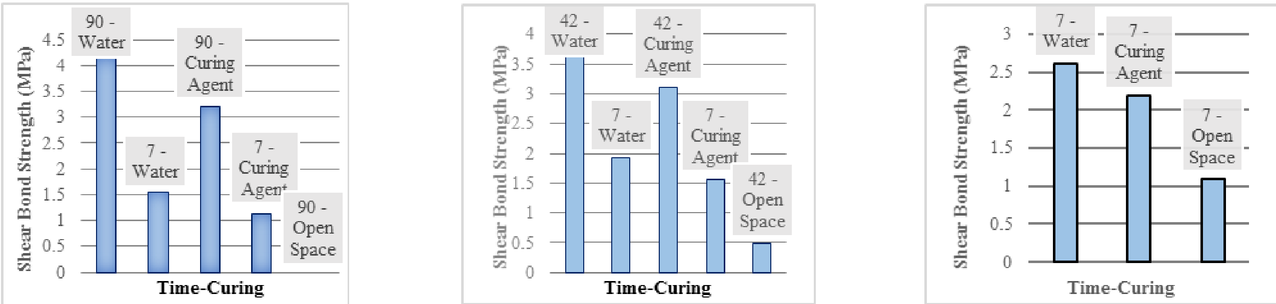



**Fig. 8.** Diagram of the M2 repair mortar shrinkage




a) 90-Day Shear Bond Strength b) 42-Day Shear Bond Strength c) 7-Day Shear Bond Strength

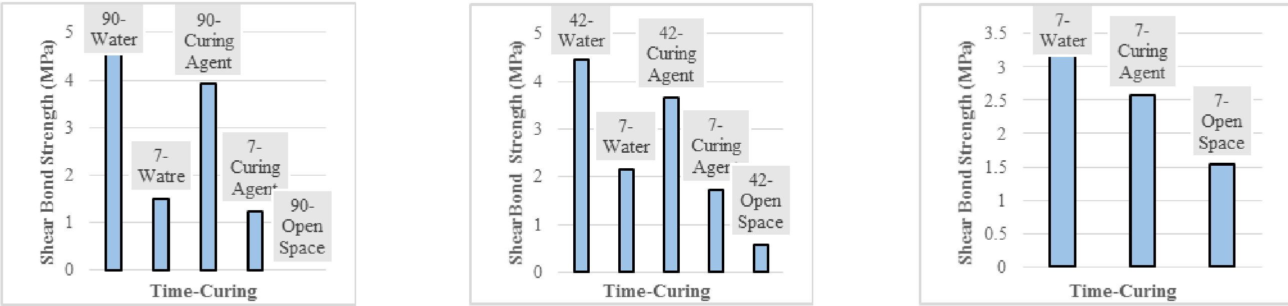
**Fig. 9.** Shear bond strength of M1 repair mortar using the "friction-transfer" method

Figure 8 shows the diagram of the M2 mortar shrinkage (0.5 : 1: 2) at different ages and under different curing operations for 7 days. From Fig. 8, it can be seen that the 90-day shrinkage value for M2 mortar cured in water, curing agents, and abandoned in open space is 0.1083, 0.1541, and 0.2679%, respectively. The amount of shrinkage for the mortar abandoned in open space is 59% higher than that cured in water. Furthermore, the amount of shrinkage in the open space increased by 30% compared to the mortar cured with curing agents. At 42 days of age, the amount of the shrinkage of these mortars in the three curings was 0.0949, 0.1414, and 0.2574%, respectively. It can be seen that the release of the specimen into the open space resulted in a 63% and 33% increase in the shrinkage, respectively, compared to the shrinkage of the specimen cured in water and with curing agents.
From Figure 7 and 8, it is observed that the lowest amount of shrinkage is related to the shrinkage of the mortars cured in water and the highest amount to the specimens abandoned in open space. The reason is that some of the moisture inside the mortar abandoned in open space is removed, thereby causing the mortar to dry out, causing the mortar to shrink. M1 mortar has the lowest amount of shrinkage due to an increase in aggregate content in these mortars compared to other mortars because aggregates usually do not shrink and cause a decrease in mortar shrinkage. An increase in cement paste in mortar causes an increase in drying shrinkage. In M2 mortar, with the highest amount of cement paste, the amount of 90-, 42-, and 28-day shrinkage increased by 18, 19, and 19.6%, respectively, compared to M1 mortar. In another study, it was found that low amounts of "water-to-cement ratio" caused a decrease in mortar shrinkage [26]. Similar research has also shown that much of the drying shrinkage occurs up to the age of 42 days, and this type of shrinkage decreases dramatically after the age of 90 days [27].

### 3.2. The Effect of Curing on Shear Bond Strength

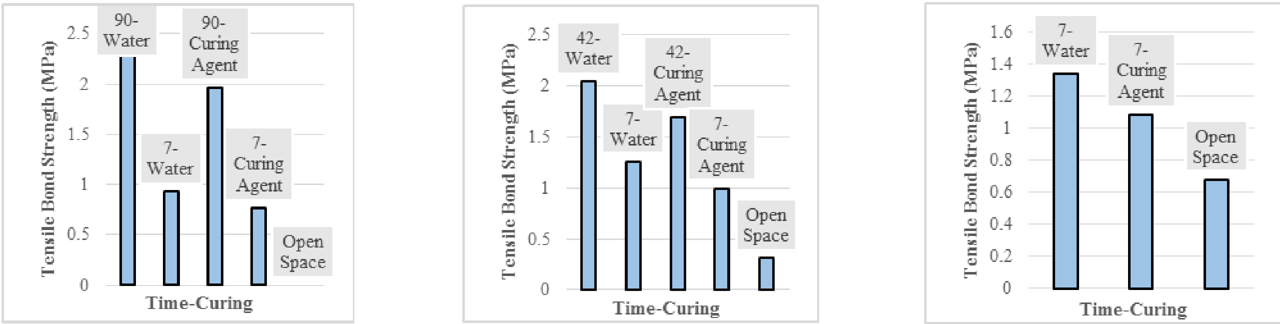
#### 3.2.1. Shear Bond Strength of the M1 Repair Mortar (0.5 : 1: 3)

Figure 9 shows the shear bond strength obtained between the concrete substrate and M1 repair mortar using the "friction-transfer" method. In this figure, the number of curing days (90, 42, and 7 days) and the type of curing (water, curing agents, and open space) are shown.
The results of the "friction-transfer" method for M1 repair mortar, shown in Figure 9, indicate that the specimens cured until the test have an incremental shear bond strength over time. The repair mortar cured in water with a shear bond strength of 7, 42, and 90 days is 2.61, 3.78, and 4.14 MPa, respectively, with an increase in shear bond strength of 58% at 7-90-day age. For the specimens cured with curing agents, the shear bond strength of 7, 42, and 90 days is 2.19, 3.1, and 3.21 MPa, respectively, with a 46% increase at 7-90-day age. However, specimens abandoned in open space have a 7- and 42-day shear bond strength of 1.089 and 1.56 MPa, respectively, whereas their shear bond strength is very low at 90 days.
Curing for a week has a major impact on the results of the "friction-transfer" method on M1 mortar. The 90-day shear bond strength for the specimens cured in water for 7 days and with curing agents is 1.56 and 1.13 MPa, respectively, while it is very low for the specimens abandoned in open space at the 90-day age. The 42-day shear bond strength for the same specimens under the above curings is 1.92 and 1.56 MPa, respectively, whereas the specimens abandoned in open space have a 0.48 MPa shear bond strength at 42 days. It is observed that curing in water for 7 days resulted in a 4-fold improvement in 42-day shear bond strength between the repair mortar and the substrate concrete. For the specimens cured with curing agents for 7 days, the 42-day shear bond strength increased 3.2-fold.




a) 90-Day Shear Bond Strength b) 42-Day Shear Bond Strength c) 7-Day Shear Bond Strength

**Fig. 10.** Shear bond strength of M2 repair mortar using the "friction-transfer" method




a) 90-Day Tensile Bond Strength b) 42-Day Tensile Bond Strength c) 7-Day Tensile Bond Strength

**Fig. 11.** Tensile bond strength of M1 repair mortar using the "pull-off" method

### 3.2.2. Shear Bond Strength of the M2 repair mortar (0.5 : 1: 2)

Figure 10 shows the shear bond strength between the substrate concrete and the M2 repair layer using the "friction-transfer" method. In this figure, the number of curing days (90, 42, and 7 days) and the type of curing (water, curing agents, and open space) are shown.

The results of the "friction-transfer" method for M2 repair mortar, shown in Figure 10, indicate that the specimens cured until the test have incremental shear bond strength over time. The repair mortar cured in water with a shear bond strength of 7, 42, and 90 days is 3.186, 4.47, and 4.72 MPa, which has a 48% increase in shear bond strength at 7-90-day age. For the specimens cured with curing agents, the shear bond strength of 7, 42, and 90 days is 2.579, 3.67, and 3.92 MPa, respectively, with a 52% increase at 7-90-day age. Nevertheless, the specimens abandoned in open space had 7- and 42-day shear bond strength of 1.531 and 0.58 MPa, respectively, whereas their shear bond strength was very low at 90 days.

Curing for a week has a major impact on the shear bond strength of the "friction-transfer" method on M2 mortar. The 90-day shear bond strength for the specimens cured in water and with curing agents for 7 days is 1.503 and 1.24 MPa, respectively, whereas the specimens abandoned in open space have a very low shear bond strength at 90 days. The 42-day shear bond strength for the same specimens under the above curings is 2.152 and 1.72 MPa, respectively, whereas the specimens abandoned in open space have a 0.579 MPa shear bond strength at 42 days. It is observed that curing in water (water curing) for 7 days resulted in a 3.7-fold 42-day shear bond strength between the repair mortar and the substrate concrete. For the specimens cured with curing agents, the 42-day shear bond strength increased three-fold.

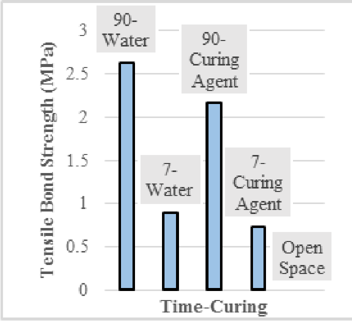
It is observed that in both mortars with different mix designs, the lack of curing causes a sharp decrease in shear bond strength as the water inside the mortar is removed and the mortar begins to dry. Moreover, the cement hydration process is not completed and the mortar shrinks, leading to shear stresses between the joint surface of the mortar and the substrate. Among the reasons for increased bond strength are an increase in gel volume due to the continuation of the cement hydration process as well as the crystalline growth at the joint boundary between the substrate concrete and the repair mortar which causes mechanical interlocking at the joint boundary between the concrete and the mortar [28]. Additionally, similar to the result obtained in this study, another study suggests that the "abandoned in open space" curing reduces the amount of adhesion and is not recommended [29].

### 3.3. The Effect of Curing on Tensile Bond Strength

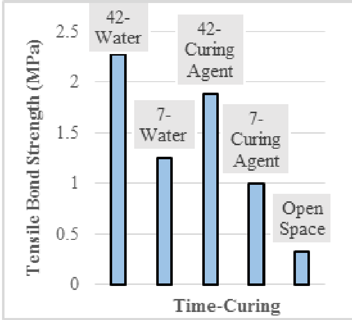
### 3.3.1. Tensile Bond Strength of M1 Repair Mortar (0.5 : 1: 3)

Figure 11 shows the tensile bond strength between the concrete substrate and the M1 repair mortar using the "pull-off" method. In this figure, the number of curing days (90, 42, and 7 days) and the type of curing (water, curing agents, and open space) are shown.

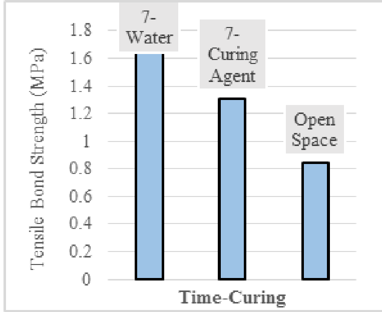
The results of the "pull-off" method for M1 repair mortar, shown in Figure 11, indicate that the specimens cured until the test have incremental tensile bond strength over time. The repair mortar cured in water has 7, 42, and 90-day tensile bond strength of 1.34, 2.04, and 2.31 MPa, with a 72% increase in tensile bond strength of 7-90 days of age. For the specimens cured with curing agents, the tensile bond strength of 7, 42, and 90 days is 1.086, 1.69, and 1.96 MPa, respectively, with an 80% increase at 7-90-day age. Notwithstanding, the specimens abandoned in open space have 7- and 42-day tensile bond strength of 0.682 and 0.31 MPa and their tensile bond strength is very low at 90 days. Compared to cured specimens, the tensile bond strength of the specimen abandoned in open space decreased by 54%.




a) 90-Day Tensile Bond Strength




b) 42-Day Tensile Bond Strength




c) 7-Day Tensile Bond Strength

**Fig. 12.** Tensile bond strength of M2 repair mortar using the "pull-off" method

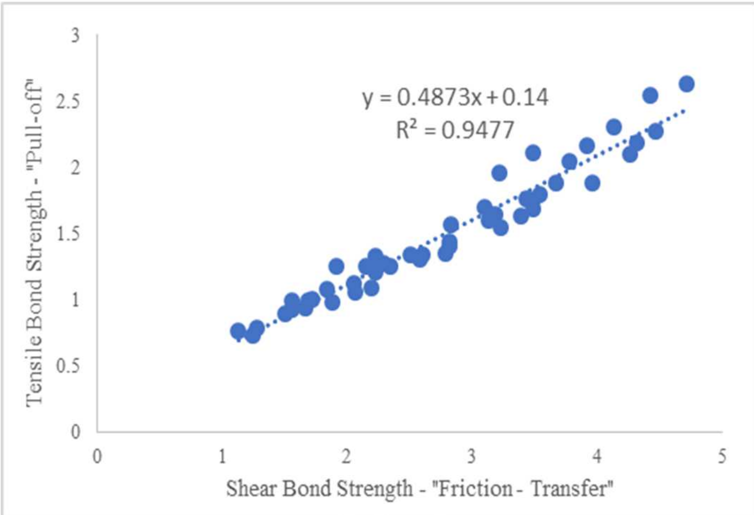



**Fig. 13.** Comparison of the results obtained from the "friction-transfer" and "pull-off" methods in MPa

Curing for a week has a major impact on the tensile bond strength of the "pull-off" method on M1 mortar. The 90-day tensile bond strength for the specimens cured in water and with curing agents for 7 days is 0.933 and 0.77 MPa, respectively, whereas the specimens abandoned in open space have a very low tensile bond strength at 90 days. The 42-day tensile bond strength for the M1 specimens under the above curings is 1.259 and 0.99 MPa, respectively, whereas the specimens abandoned in open space have a 0.314 MPa tensile bond strength at 42 days. It is observed that curing in water for 7 days resulted in a 4-fold 42-day tensile bond strength between the repair mortar and the substrate concrete. For the specimens cured with curing agents, the 42-day tensile bond strength increased by 3.1-fold.

### 3.3.2. Tensile Bond Strength of M2 Repair Mortar (0.5 : 1: 2)

Figure 12 shows the tensile bond strength between the concrete substrate and the M2 repair mortar using the "pull-off" method. In this figure, the number of curing days (90, 42, and 7 days) and the type of curing (water, active ingredients, and open space) are shown.

The results of the "pull-off" method for M2 repair mortar, shown in Figure 12, indicate that the specimens cured in water and with curing agents until the test have an incremental tensile bond strength over time. The repair mortar cured in water has 7, 42, and 90-day tensile bond strength of 1,643, 2.27, and 2.63 MPa, respectively, with tensile bond strength increasing by 61% at 7-90-day age. For the specimens cured with curing agents until the test, the tensile bond strength of 7, 42, and 90 days is 1.311, 1.88, and 2.16 MPa, respectively, which is 65% higher at 7-90-day age. Nonetheless, the specimens abandoned in open space have a 7- and 42-day tensile bond strength of 0.743 and 0.32 MPa, respectively, and their tensile bond strength is very low at 90 days. Compared to the specimens cured until the test, the tensile bond strength of the specimens abandoned in open space decreased by 61%.

Curing for a week has a major impact on the tensile bond strength of the "pull-off" method on M2 repair mortar. The 90-day tensile bond strength for the specimens cured in water and with curing agents for 7 days is 0.897 and 0.74 MPa, respectively, whereas the specimens abandoned in open space have a very low tensile bond strength at 90 days. The 42-day tensile bond strength for the M2 specimens under the above curings is 1.251 and 1 MPa, respectively, whereas the specimens abandoned in open space have 0.323 MPa tensile bond strength at 42 days. It is observed that curing in water for 7 days resulted in a 3.87-fold 42-day tensile bond strength between the repair mortar and the substrate concrete. For the specimens cured with curing agents, the 42-day tensile bond strength increased by 3.1-fold.

As with the results of the "friction-transfer" method, it is also observed that in both mortars with different mix designs, the lack of curing causes a sharp decrease in the tensile bond strength since the water inside the mortar is removed and the mortar begins to dry. In addition, the cement hydration process is not completed and the mortar shrinks, leading to shear stresses between the joint surface of the mortar and the substrate.

**Table 6.** Results of the compressive strength, the "friction-transfer" and "pull-off" tests (in MPa)

| Test Method | 3-Day | | | 7-Day | | | 28-Day | | | 42-Day | | | 90-Day | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Water | Curing Agent | Open Space | Water | Curing Agent | Open Space | Water | Curing Agent | Open Space | Water | Curing Agent | Open Space | Water | Curing Agent | Open Space |
| Compressive Strength | 2.33 | 19.2 | 13.2 | 34.1 | 30.2 | 20.9 | 47.6 | 40.9 | 28.6 | 51.2 | 43 | 30.9 | 54.4 | 45.1 | 32.1 |
| "Friction-Transfer" | 2.36 | 1.89 | 1.44 | 3.61 | 3.05 | 2.31 | 4.69 | 3.84 | 2.97 | 5.19 | 4.2 | 3.35 | 5.64 | 4.56 | 3.55 |
| "Pull-Off" | 1.22 | 1.06 | 0.76 | 1.77 | 1.61 | 1.19 | 2.29 | 1.99 | 1.49 | 2.82 | 2.4 | 1.76 | 3.17 | 2.74 | 1.88 |

**Table 7.** The relationship between the compressive strength as well as the shear and tensile bond strength (in MPa)

| Curing | Test | 7-day | 42-day | 90-day | Average Bond Strength-Compressive Strength Ratio(%) |
|---|---|---|---|---|---|
| | Compressive Strength | 34.1 | 51.2 | 54.4 | - |
| Water | Shear Bond Strength | 3.18 | 4.47 | 4.72 | 8.9 |
| | Tensile Bond Strength | 1.64 | 2.27 | 2.63 | 4.5 |
| | Compressive Strength | 30.2 | 43 | 45.1 | - |
| Curing Agent | Shear Bond Strength | 2.58 | 3.67 | 3.92 | 8.6 |
| | Tensile Bond Strength | 1.31 | 1.88 | 2.16 | 4.4 |
| | Compressive Strength | 20.9 | 30.9 | 32.1 | - |
| Open Space | Shear Bond Strength | 1.53 | 0.58 | - | 4.1 |
| | Tensile Bond Strength | 0.84 | 0.32 | - | 2.5 |

### 3.4. The Relationship Between the Shear and Tensile Bond Strength Derived from the "Friction-Transfer" and "Pull-Off" Methods

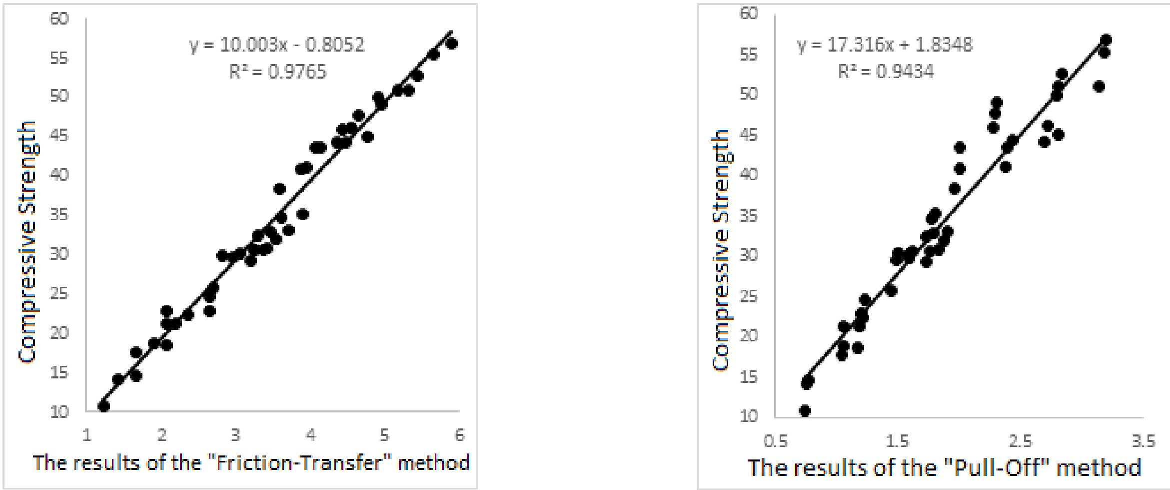
Figure 13 shows the relationship between the shear bond strength obtained by the "friction-transfer" method and the tensile bond strength obtained by the "pull-off" method for the cement-based (cementitious) mortars tested in this study.

From Figure 12, it can be seen that the coefficient of determination between the results of the "pull-off" and "friction-transfer" methods is equal to 0.95. Furthermore, the correlation coefficient between the two methods is 0.97. Given the high correlation coefficient between the results obtained from the "pull-off" and "friction-transfer" methods, one can easily obtain results equivalent to one from the other. Shear bond strength is often greater than tensile bond strength [25]. In this study, the shear bond strength obtained from the "friction-transfer" method is greater than that obtained from the "pull-off" method.

### 3.5. The Relationship Between the Mechanical Properties of the Repair Mortar and the Results of the "Friction-Transfer" and "Pull-Off" Methods

#### 3.5.1. Compressive Strength of the Repair Mortar

This section examines the compressive strength of M2 repair mortar at the ages of 3, 7, 28, 42, and 90 days undergoing curing in water, with curing agents and abandoned in open space until the time of testing. Table 6 shows the results of the "friction-transfer" and "pull-off" tests with the compressive strength of the mortars. In this table, the results of the compressive strength are the mean of 5 tests and each of the results of "friction-transfer" and "pull-off" methods is the average of three tests. From Table 6, it can be seen that curing increases the compressive strength of the repair mortar by completing the cement hydration process inside the mortar to prevent moisture from exiting the mortar. The 90-day compressive strength of repair mortar in curing with water and with curing agents is 2.33 and 2.35 times the 3-day compressive strength, respectively. However, the specimens abandoned in open space have acquired less strength over time due to moisture excretion inside the mortar and incomplete hydration process inside it. The 3-, 7-, 28-, 42-, and 90-day compressive strengths of mortars cured in water were 1.77, 1.63, 1.66, 1.65, and 1.7 times the compressive strengths of mortars abandoned in open space, respectively. Moreover, for the specimen cured with curing agents compared to the specimen abandoned in open space, it is 1.45, 1.44, 1.43, 1.39, and 1.4, respectively at the age mentioned above. The results of the "friction-transfer" and "pull-off" tests also have the same incremental trend.




a) Compressive Strength - "Friction-Transfer"

b) Compressive Strength - "Pull-Off"

**Fig. 14.** The relationship between the compressive strength of the repair mortar and the results of the "friction-transfer" and "pull-off" tests (in MPa)

Table 7 shows the relationship between the compressive strength as well as the shear and tensile bond strength obtained by the "friction-transfer" and "pull-off" methods.

From Table 7, it can be seen that the mortars cured in water and with curing agents have approximately the same ratio between the compressive strength as well as the shear and tensile bond strength obtained by the "friction-transfer" and "pull-off" methods. For the mortars cured in water, the ratio of shear and tensile bond strength to the compressive strength of the mortar is 8.9% and 4.5%, respectively. For the mortar cured with curing agents, these ratios are 8.6 and 4.4%, respectively. However, for the specimens abandoned in open space, both compressive strength and bond strength are reduced compared to specimens cured due to the evaporation of moisture inside the mortar and incomplete hydration process, but the ratio of reduced bond strength is higher, thereby reducing the ratio of shear bond strength and tensile bond strength to compressive strength to 4.1 and 2.5. Moreover, another study estimated the tensile bond strength to be about 6.2% of the compressive strength [30]. Figure 14 shows the relationship between the compressive strength of the repair mortar and the results of the "friction-transfer" and "pull-off" tests.

From Figure 14a, it can be seen that the results of the "friction-transfer" test with the compressive strength of the repair mortar have a coefficient of determination of 0.97 and a correlation coefficient of 0.98. In addition, according to Figure 14b, the results of the "pull-off" test with the mortar compressive strength have a coefficient of determination of 0.94 and a correlation coefficient of 0.97. Given the high correlation coefficient between the compressive strength of the repair mortar and the results of the above methods, it is easy to determine the compressive strength of the mortar using the "friction-transfer" and "pull-off" tests.

### 3.5.2. Tensile Strength of the Repair Mortar

This section examines the tensile strength of M2 repair mortar at the ages of 3, 7, 28, 42, and 90 days undergoing curing in water, with curing agents and abandoned in open space until the time of testing. Table 8 shows the results of the "friction-transfer" and "pull-off" tests with the tensile strength of the mortars.

From Table 8, it can be seen that curing has caused an increase in the tensile strength of the repair mortar by completing the cement hydration process inside the mortar to prevent moisture from exiting the mortar. The 90-day repair mortar tensile strength of curing in water and with curing agents is 2.32 and 2.27 times the 3-day tensile strength, respectively. Nevertheless, the specimens abandoned in open space have acquired less strength over time due to moisture excretion from the mortar and the incomplete hydration process inside it. The 3-, 7-, 28-, 42-, and 90-day tensile strength of the mortar cured in water were 1.96, 1.92, 2, 1.89, and 2.07 times the tensile strength of the mortar released in the open space, respectively. Additionally, for the specimens cured with curing agents compared to the specimen abandoned in open space, it is 1.56, 1.55, 1.64, 1.58, and 1.69, respectively. The results of the "friction-transfer" and "pull-off" tests also have the same incremental trend. In addition, comparing the tensile and compressive strength of the mortar shown in Tables 6 and 8 suggests that the tensile strength of the repair mortar is on average 7.5% of its compressive strength.

Table 9 shows the relationship between the tensile strength and shear and tensile bond strength obtained by the "friction-transfer" and "pull-off" methods.

From Table 9, it can be seen that the mortars cured in water and with curing agents have approximately the same ratio between the tensile strength and shear and tensile bond strength obtained by the "friction-transfer" and "pull-off" methods. For the mortars cured in water, shear and tensile bond strength are 1.11 and 0.58 times the tensile strength of mortar, respectively. These ratios for the mortar cured with curing agents are 1.12 and 0.59. Nonetheless, for the specimens abandoned in open space, both tensile strength and bond strength are reduced compared to the specimens cured due to the evaporation of moisture inside the mortar and incomplete hydration process, but the ratio of reduced bond strength is greater.

Figure 15 shows the relationship between the tensile strength of the repair mortar and the results of the "friction-transfer" and "pull-off" tests.

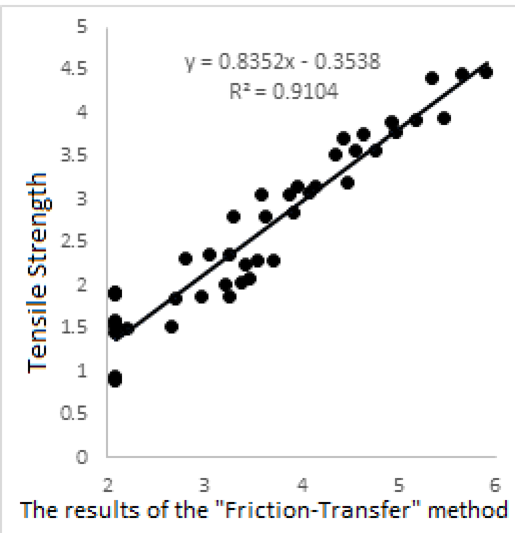
From Figure 15a, it can be seen that the results of the "friction-transfer" test with the tensile strength of the repair mortar have a coefficient of determination of 0.91 and a correlation coefficient of 0.95. In addition, according to Figure 15b, the results of the "pull-off" test with the mortar tensile strength have a coefficient of determination of 0.93 and a correlation coefficient of 0.96. Given the high correlation coefficient between the tensile strength of the repair mortar and the results of these methods, it is easy to determine the tensile strength of the mortar using in-situ "friction-transfer" and "pull-off" tests.

**Table 8.** Results of tensile strength, the "friction-transfer" and "pull-off" test (in MPa)

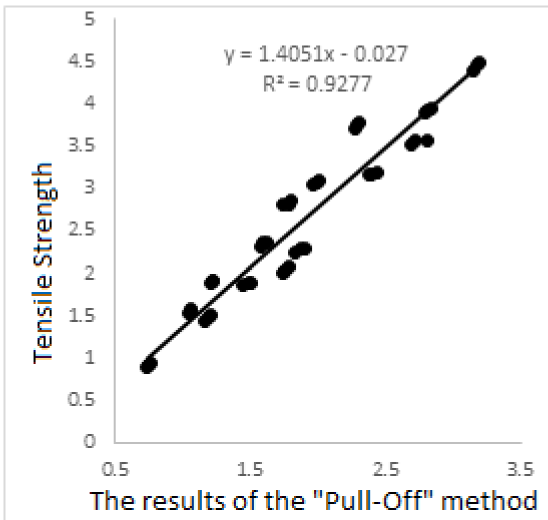
| Test Method | 3-Day | | | 7-Day | | | 28-Day | | | 42-Day | | | 90-Day | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Water | Curing Agent | Open Space | Water | Curing Agent | Open Space | Water | Curing Agent | Open Space | Water | Curing Agent | Open Space | Water | Curing Agent | Open Space |
| Tensile Strength | 1.91 | 1.56 | 0.92 | 2.82 | 2.35 | 1.49 | 3.74 | 3.07 | 1.87 | 3.92 | 3.17 | 2.04 | 4.45 | 3.55 | 2.27 |
| "Friction-Transfer" | 2.36 | 1.89 | 1.44 | 3.61 | 3.05 | 2.31 | 4.69 | 3.84 | 2.97 | 5.19 | 4.2 | 3.35 | 5.64 | 4.56 | 3.55 |
| "Pull-Off" | 1.22 | 1.06 | 0.76 | 1.77 | 1.61 | 1.19 | 2.29 | 1.99 | 1.49 | 2.82 | 2.4 | 1.76 | 3.17 | 2.74 | 1.88 |

**Table 9.** The relationship between the tensile strength and shear and tensile bond strength (in MPa)

| Curing | Test | 7-Day | 42-Day | 90-Day | Average Bond Strength-Compressive Strength Ratio(%) |
|---|---|---|---|---|---|
| | Tensile Strength | 2.82 | 3.92 | 4.45 | - |
| Water | Shear Bond Strength | 3.18 | 4.47 | 4.72 | 1.11 |
| | Tensile Bond Strength | 1.64 | 2.27 | 2.63 | 0.58 |
| | Tensile Strength | 2.35 | 3.17 | 3.55 | - |
| Curing Agent | Shear Bond Strength | 2.58 | 3.67 | 3.92 | 1.12 |
| | Tensile Bond Strength | 1.31 | 1.88 | 2.16 | 0.59 |
| | Tensile Strength | 1.49 | 2.04 | 2.27 | - |
| Open Space | Shear Bond Strength | 1.53 | 0.58 | - | 0.66 |
| | Tensile Bond Strength | 0.84 | 0.32 | - | 0.32 |




a) Tensile Strength - "Friction-Transfer"




b) Tensile Strength - "Pull-Off"

**Fig. 15.** The relationship between the tensile strength of the repair mortar and the results of the "friction-transfer" and "pull-off" tests (in MPa)

### 3.6. Modeling and Nonlinear Analysis of "Friction-Transfer" and "Pull-Off" Tests

There is a wide range of non-elastic behavioral properties of materials for use in various issues in Abaqus. This software describes the non-elastic behavioral properties of concrete completely separately. One of the Abaqus models for concrete analysis is the concrete damage plasticity (CDP) model used in this part of the study. The CPD model is a robust model used for different loadings, which offers concrete behavior more realistically by expressing individual tensile and compressive behavior of concrete. It is based on a plasticity damage model according to the model proposed by Lobliner [31] and modified by Lee and Fenos [32]. It is embedded in Abaqus/Standard and Abaqus/Explicit environments for modeling concrete and other quasi-brittle materials in various elements of beams, trusses, shells, and solids.

In CPD theory, the evolution of the yield (or failure) surface is controlled using hardening variables ($\varepsilon_t^{pl}$, $\varepsilon_c^{pl}$) linked to failure mechanisms under compression and tension loading, respectively. ($\varepsilon_t^{pl}$, $\varepsilon_c^{pl}$) are equivalent plastic strains. Figures (16) and (17) show the stress-strain curves of concrete in uniaxial tension and compression. Under uniaxial tension, the stress-strain curve changes linearly to the breakdown stress point $\sigma_{t_0}$ associated with the onset and extension of micro-cracks in concrete. Then, the breakdowns come in the form of visible cracks displayed as softening curves in the stress-strain space. Due to uniaxial compression, the response will be elastic until it reaches the yield point $\sigma_{c_0}$. The behavior in the plastic region is usually expressed as a hardening curve. Finally, by reaching the final stress point $\sigma_{c_u}$, the curves turn into softening curves.

In defining the behavior of concrete after cracking under tension, the software assumed the compressive hardening reduction value of the $wc$ coefficient to be 1 to fully reduce the compressive hardening during crack closure (after cracking under tension). In contrast, the $wt$ coefficient was assumed to be 0 to ignore the tensile hardening reduction. Initially, "pull-off" and "friction-transfer" test components such as adhesive, 150-mm concrete cubic specimens, and metal cylinders were modeled. To do this, the "Create Part" command was used. The "Create Material" command in the "Module Property" part was used to introduce the material, the stress-strain curve, and the required values. The assembly of components and meshing were also executed using commands available in the software. In the "friction-transfer" test, the supports were defined in modeling according to Figure 18a because the concrete specimens were placed inside a steel frame in the laboratory enclosing the concrete around from the bottom to a height of 30 mm. Moreover, in the "pull-off" method, two oblique strips were partitioned on the model surface to be aligned in height to define the supports in the software according to Figure 18b because the device is mounted on a concrete specimen.

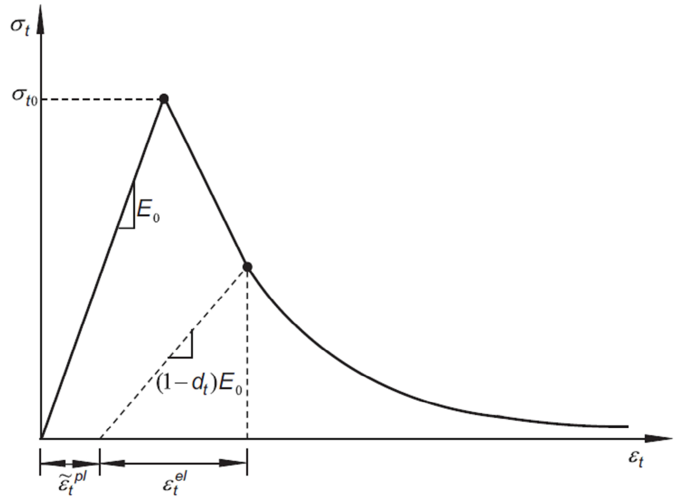



**Fig. 16.** Concrete response under uniaxial loading in tension

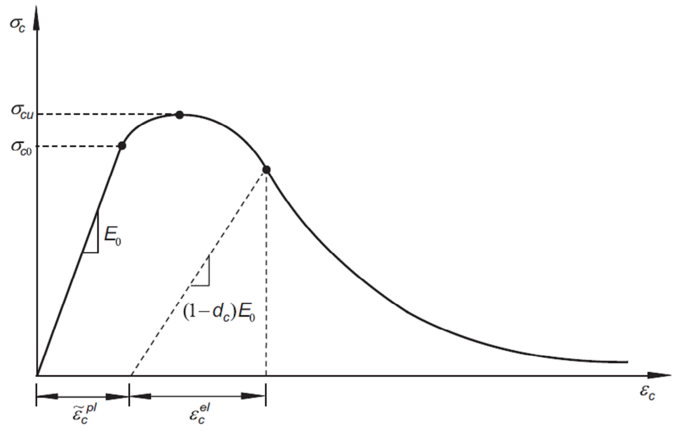
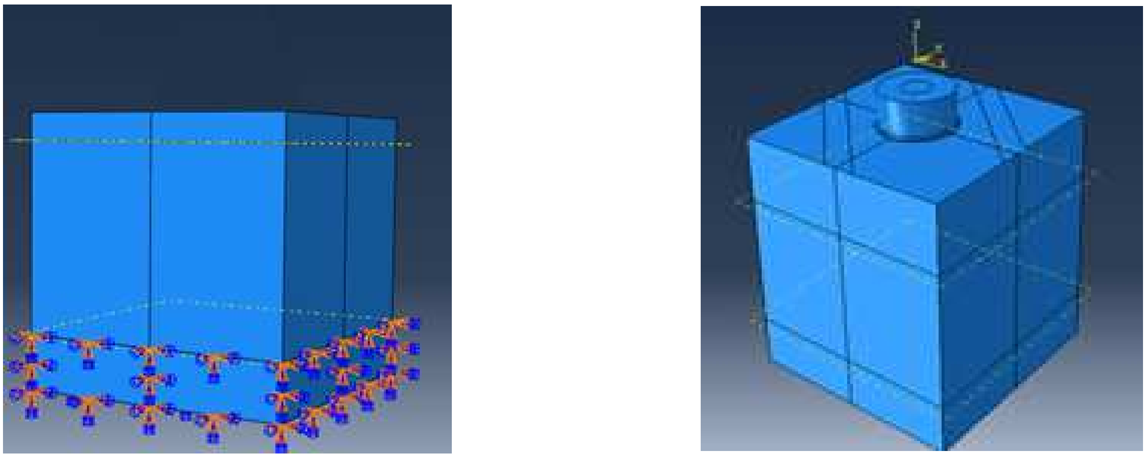



**Fig. 17.** Concrete response under uniaxial loading in compression



a) Boundary conditions in the "friction-transfer" test

b) Boundary conditions in the "pull-off" test

**Fig. 18.** Definition of boundary conditions

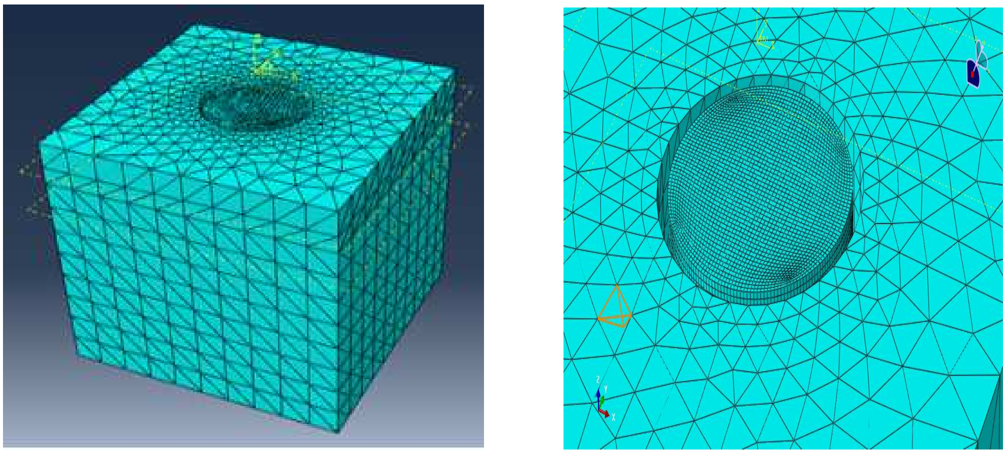


**Fig. 19.** Specimen partitioning in the "friction-transfer" test

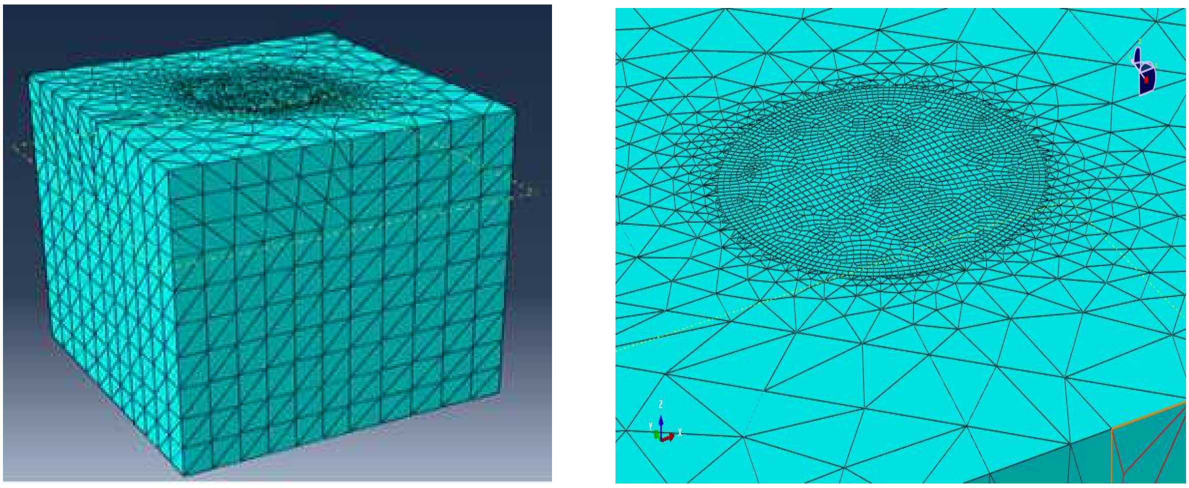


**Fig. 20.** Specimen partitioning in the "pull-off" test

The important point in the meshing of the specimens is convergence. The results obtained from solving a problem in the FEM are always dependent on the size of the meshes and the size of the elements used. The problem-solving converges to a single solution by reducing the dimensions of the elements. However, the meshing size improvement should be done so as not to cause a sharp increase in computational volume. Since finite element solutions are dependent on the meshing size, the meshing convergence must always be checked in areas of the model where the values of stress, strain, or any other parameter must be accurately calculated. The meshing size can be considered large enough in areas far from stress concentration points. In the "friction-transfer" test, the partitioning of the concrete is done in a combination of two types of elements, namely C3D8R and C3D4. The core component compressed or tensioned with an 8-node cubic element was partitioned using the reduced integration C3D8R. In this section, the element size is assumed to be 1 mm. After convergence, it was selected between 0.5, 1, and 2 mm. Element lateral sides were partitioned with a 4-node continuous tetrahedral element, with a maximum element size of 15 mm at the sides and a minimum element size of 1 mm at locations connected to the principal elements (Figure 19).

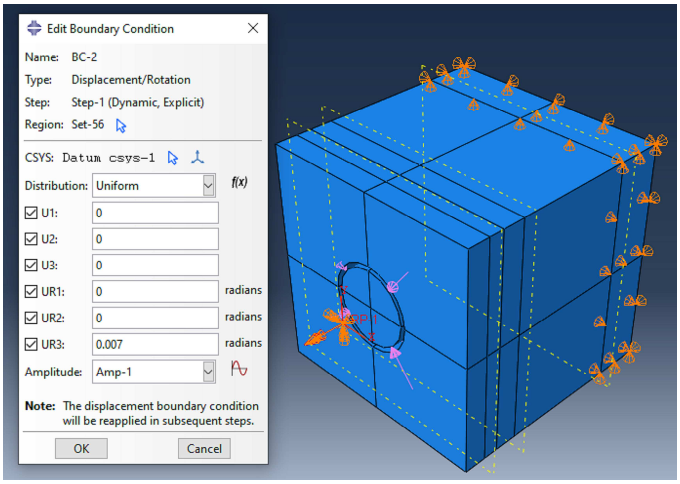
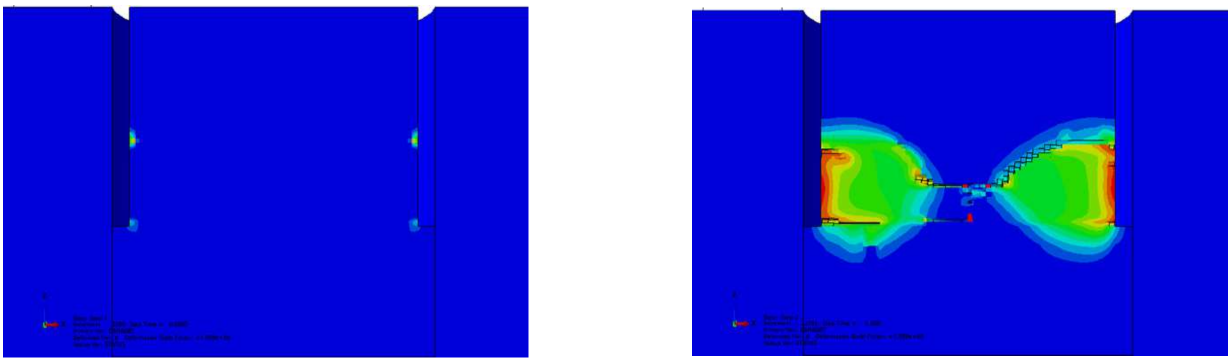



**Fig. 21.** Torsional moment applied to the core in the "friction-transfer" test


a) "Friction-Transfer"

b) "Pull-off"

**Fig. 22.** Modeling Sample Loading



a) Crack emergence moment

b) Core failure moment

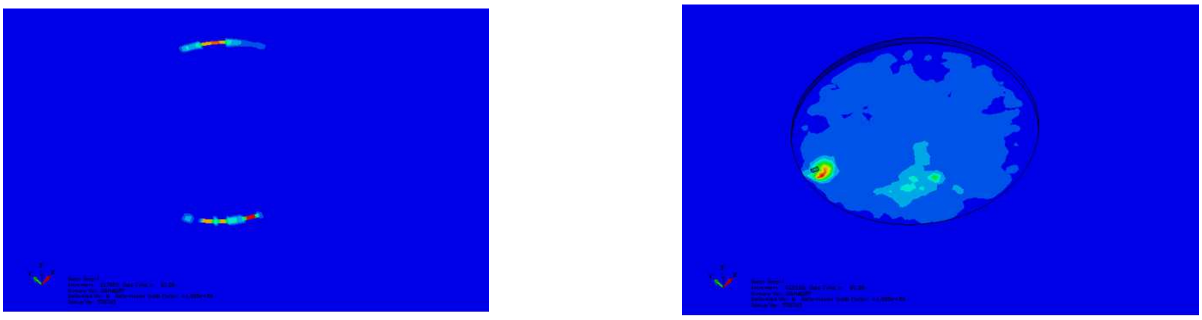
**Fig. 23.** Core failure in the "friction-transfer" test

In the "pull-off" test, concrete segment partitioning is done by combining two elements, i.e., C3D8R and C3D4. The core of the segment curved or tensioned was partitioned with an 8-node cubic element using the reduced integration C3D8R. In this section, the element size is assumed to be 1 mm. After convergence, it was selected between 0.5, 1, and 2 mm. Lateral sections with a 4-node continuous tetrahedral element were partitioned with a maximum element size of 15 mm on the sides and a minimum element size of 1 mm in locations connected to the principal elements (Figure 20). The adhesive segment was partitioned with a 2mm element with a C3D8R type element and the steel segment with an overall 2mm element. In the steel segment, the elements were assumed to be 10 mm in the axial direction.

The latest Abaqus version released in 2019 was used for modeling. Earlier versions of this software did not allow the failure of the elements to be observed after loading in the CPD method. Nevertheless, in version 2019, the capability of observing "element death" on the specimens has been added to the software. The specimen tested in the laboratory was modeled with a compressive strength of 47.6 MPa, which failed in the "friction-transfer" test at a 115 N torsional moment and at 4500 N in the pull-off test.

In the "friction-transfer" test, a torsional moment of 0.007 rad was applied as the rotational shift around the axis of the core to the core environment using the coupling constraint, as shown in Fig. 21. Furthermore, in the "pull-off" test, the middle section of the steel cylinder is drawn up to a diameter of 20 mm upwards along the axis to a reference point designated as the pulling jack.

Figure 22a shows the torsional moment value applied to the core in the "friction-transfer" test against its rad value. From Figure 22a, it can be seen that the value of the final moment, the factor contributing to the core failure, is 108 Nm, highly consistent with the laboratory result on the same specimen, i.e., 115 Nm. Moreover, in the "pull-off" test, a failure occurs at a tensile force of 4555 N, which is highly consistent with the result obtained in the laboratory on the same specimen, i.e., 4500 N, as shown in Figure 22b.



a) Crack emergence moment b) Core failure moment

**Fig. 24.** Specimen failure in the "pull-off" test

In the "friction-transfer" test, the maximum moment tolerated by the model is 108 Nm. The first cracks appear in the specimen at a moment of 46 Nm at the edges of the specimen and from the corners under the highest momentum. The lower corner created by the coring and the higher value, where the edge of the metal clamp is located, act as a notch. The momentum increases with an increase in the rotation until it reaches 107 kN when cracks collide and breakdown occurs. From this point onwards, an increase occurs in the rate of breakdown due to a decrease in cross-sectional area and core strength, which eventually results in complete failure (Figure 23).

In the "pull-off" test, the initial cracks appear at the edges of the steel cylinder-to-concrete junction at 2448 N. The crack has grown dramatically at 3814 N. Finally, at 4555 N, the model reaches the critical force, followed by an increase in crack growth and a decrease in process force until the model reaches complete failure (Figure 24).

The finite element method results are highly consistent with the experimental results. In the "friction transfer" test, maximum shear stresses occur around the core, causing the failure to occur in these areas the finite element modeling results, and the failure angle to be approximately 45 degrees. In the experimental, the core failure has a 45-degree angle around the core. The modeling results also showed that the cracks first occur around the core and then expand toward the center at an angle of about 45 degrees, finally, when they reach each other and the core failure occurs. The finite element method results also show that the maximum moment, which caused the failure in the sample, is 107 Nm in the friction transfer test while the maximum moment is 115 Nm in the experimental. It is observed that the laboratory results are very close to those obtained in the finite element method. Also, in the "pull-off" test, the finite element method showed that the final force, which caused the core failure, is 4555 N. while the final force applied to the core is 4500 N in the experimental. Similar to the friction transfer method, it is concluded that the experimental results are highly consistent with the finite element.

## 4. Conclusion

The significant findings of this paper can be summarized as below:

- Lack of curing results in an increase in the shrinkage of repair mortars, which results in shear stresses at the joint surface of the repair mortar and the substrate concrete and a decrease in shear and tensile bond strength obtained by the "friction-transfer" and "pull-off" methods.
- 90-day shrinkage in the specimens abandoned in open space is 59.6% and 39% higher than water-submerged specimens, respectively. An increase in shrinkage caused the shear and tensile bond strength of the 90-day of the specimens abandoned in open space to be equal to zero.
- Due to the high volume of aggregate in the repair mortar mix, which makes up about 60% of it, an increase in the amount of aggregate in the repair mortar causes a decrease in drying shrinkage.
- Curing for 7 days has a major impact on the adhesion of the joint surface of the mortar and the substrate concrete. The 42-day shear and tensile bond strength of these specimens are, on average 3.5 and 3.6 times those of the specimens abandoned in open space, respectively. Moreover, the shear and tensile bond strength of these specimens at 90 days are on average 1.399 and 0.853 MPa, respectively, while equal to zero for the specimens abandoned in open space at 90 days of age.
- In all tests, an increase in curing time increased shear and tensile bond strength between the repair layer and the concrete substrate resulting from the "friction-transfer" and "pull-off" methods, respectively.
- Given the high coefficient of determination and the correlation coefficient between the results of the "friction-transfer" and "pull-off" methods for the repair mortars tested in this study, a cheap "friction-transfer" device can be used to obtain the bond strength between the repair mortar and the concrete substrate, rather than an expensive "pull-off" device.
- The results indicate a direct relationship between the tensile and compressive strength of repair mortar and the shear and tensile bond strength obtained from the "friction-transfer" and "pull-off" tests.
- Given the high coefficient of determination and the correlation coefficient between the results of the "friction-transfer" and "pull-off" methods and the compressive and tensile strength of the repair mortar, the in-situ "friction-transfer" and "pull-off" methods can be used to obtain the tensile and compressive strength of mortars, rather than using in-vitro tests.
- After modeling the "friction-transfer" and "pull-off" tests and performing a nonlinear analysis using Abaqus, it was found that there is a high agreement between the results of the nonlinear analysis and the laboratory results such that the difference between the two states is very low.

## Author Contributions

A.S. Varzaneh conducted the experiments, analyzed the empirical results, developed the mathematical modeling and examined the theory validation; M. Naderi planned the scheme, initiated the project, and suggested the experiments; The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed, and approved the final version of the manuscript.

## Acknowledgments

Not applicable.

## Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

## Funding

The authors received no financial support for the research, authorship, and publication of this article.

## Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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**How to cite this article:** Saberi Varzaneh A., Naderi M. Experimental and Finite Element Study to Determine the Mechanical Properties and Bond Between Repair Mortars and Concrete Substrates, *J. Appl. Comput. Mech.*, 8(2), 2022, 493–509. https://doi.org/10.22055/JACM.2020.32921.2101