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Numerical and Experimental Study of In-Situ Methods to Evaluate the Mechanical Properties of Fiber-Reinforced Mortars

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ABSTRACT: Nowadays, it is significantly important to perform in situ methods to evaluate the quality of cement materials. The present study tried to use semi destructive "friction transfer" and "Pull-off" methods to evaluate the compressive and flexural strength of polypropylene fiber-reinforced cement mortars at different ages. Therefore, the relationship between compressive and flexural strength of fiber-reinforced mortars and readings of "friction transfer" and "Pull-off" tests is presented here. Results of these tests were extracted at ages of 3, 7, 28, 42, and 90 days and compared with the compressive and flexural strengths of the fiber-reinforced mortars. The calibration curve graphs were presented by linear and power regression analysis. A total of 120 cubic specimens with a size of 50 mm, 60 prismatic specimens with a size of 40*40*160 mm, and 80 cubic specimens with a size of 150 mm were fabricated for compressive, flexural, and in-situ tests, respectively. Also, the distribution of stresses and the propagation of crack were studied through the abovementioned tests using the finite element method and modeling with the ABAQUS software, and compared with the experimental results. The results showed that there was a high correlation between the readings of the "friction transfer" and "Pull-off" tests, and between the compressive and flexural strengths of the fiber-reinforced cement mortars. Moreover, the addition of fibers improved the behavior of cement mortars subjected to compression, and the finite element method was highly consistent with the experimental results.

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1- Introduction

Materials made with cement, such as mortar and concrete, are widely used construction and structural materials. Cementitious materials are considered to be brittle, non-homogeneous, and anisotropic contrary to steel, and their strength behavior is different in compression and tension; besides, their tensile strength is much lower than their compressive strength. Therefore, some solutions must be adopted to improve the cementitious behavior in tension, one of which is the application of fibers within the cementitious mixture. Fibers have commonly been used for a long time. For example, straw is used in the mortar to prevent cracking. Also, the use of fibers causes an improvement in the concrete behavior under the exerted compressive stresses [1, 2], and has a positive effect on the stress-strain diagram [3]. In research by Shakir et al. [4], it was shown that adding 0.5% by volume of fibers caused an increase in tensile strength of mortar by 7.21%. Mesbah et al. [5] investigated the effect of polypropylene fibers on the crack formation in mortars and observed that adding polypropylene fibers caused a delay in the propagation of cracks in the mortar and prevented their opening. Sadrmomtazi et al. [6] studied the effect of polypropylene fibers on the mortars and concluded that these fibers could improve the compressive and flexural strengths of mortars. However, adding more than 0.3% by volume of fibers causes a negative effect on the mortars. In many studies, it is concluded that adding extra fibers has negative effects on the properties of cementitious materials [7-9]. In this research, therefore, the number of fibers was selected equal to 0.3% by volume of mortar to determine their positive effect on the results of in situ methods.

Furthermore, new inorganic materials have been employed to improve the behavior and adhesion of mortar and concrete in recent years. Fiber-reinforced polymers and fiber-reinforced cementitious matrixes have achieved numerous successes in structural strengthening and repair as they offer advantages over traditional materials. Easy use and high strength-to-weight ratios are among the main success factors of these new technologies [10]. Glass fiber-reinforced polymers are another type of such material. They can, for example, be utilized to strengthen the columns of reinforced concrete structures [11]. Steel-reinforced grout is another new repair material that improves the adhesion to concrete surfaces [12].

Considering that the experimental methods could not represent an appropriate assessment of the strength acquiring process at different ages, the use of in situ methods for

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Table 1. Fibers specifications.

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

determining the strength of mortars is of great importance. The measurement methods are divided into three groups of “destructive”, “semi-destructive”, and “non-destructive” tests. Drilling cores [13] is a destructive method that has some defects such as a high cost, limited iteration number, and considerable damage to the structure. Also, results obtained from coring exhibit a lower compressive strength than the real one in these materials [14]. Another destructive method is the “Pull-out” test [15], which could cause damage to the structural elements. Non-destructive tests include ultrasonic pulse velocity [16] and Schmidt hammer (with its rebound number output) [17] tests. These methods could indirectly assess the strength of materials. The “twist-off” [18], “friction transfer” [19], and “Pull-off” tests [20] are some of the semi-destructive methods.

In this research, the semi-destructive methods of “friction transfer” and “Pull-off” tests were employed for assessing the compressive and flexural strengths of mortars reinforced with polypropylene fibers. In the “Pull-off” test, a steel-made cylinder with a 50-mm diameter is attached to the mortar surface and a tensile force is exerted upon the cylinder using a tension-based apparatus until it experiences rupture. In the “friction transfer” method, first, a core is taken from the surface of the specimen with a 50-mm diameter and 25-mm height. Then, the metallic apparatus is fixed upon the core and a certain amount of torque is applied to the core using an ordinary torque-meter until it undergoes rupture. As the rupture occurs within the specimen body in this test, its results are more accurate than those of the non-destructive tests, where the mortar strength is determined indirectly. In several cases of previous studies, the “friction transfer’ test was applied for assessing the concrete strength [21-22], rock strength [23], and bituminous pavement [24]. Also, this test is used for assessing the adhesion of mortar to the concrete substrate [25-26].

Two types of cementitious mortars were used for performing these tests. After adding 0.3% by volume of polypropylene fibers to the mortars, the obtained results were compared to fiberless mortars. The compressive and flexural strengths were determined for fiberless and fiber-reinforced mortars and the results were compared with readings from the “friction transfer” and “Pull-off” tests. The relationships between the in situ and experimental tests were determined using the linear and exponential regression methods, followed by drawing calibration diagrams. The obtained results revealed the appropriateness of the “friction transfer” and “Pull-off” tests for assessing the strength of fiber-reinforced and fiberless cementitious mortars. Also, the fiber-reinforced and fiberless mortars were modeled via the finite element method using the ABAQUS software to investigate their behavior. The results showed good compatibility between the experimental results and those obtained from the finite element method.

Although experimental material strength tests have a long history, in-situ tests have been paid particular attention in recent years. The necessity of developing in-situ tests arises from the increased number of new materials and unexpected failures in several buildings and structures. Thus, not only are experimental tests required, but it is also necessary to develop tests to measure the in-situ strengths of materials in the service sites of structures. Thus, the present study introduces the semi-destructive in-situ friction-transfer test and evaluates correlations between the results of the friction-transfer test and those of standard experimental tests. As a result, by using the friction-transfer test, the strengths of fiber-reinforced materials, which are frequently utilized as repair layers, can be measured in the sites of projects at different ages and with minimum structural destruction. The friction-transfer test has been employed to evaluate the strengths of concrete and typical mortars. Thus, the present study plans tests on the use of the friction-transfer test for evaluating the strengths of fiber-reinforced mortars.

2- Experimental Activities

2- 1- Materials

To fabricate typical mortars and polypropylene fiber-reinforced mortars, sand with a maximum aggregate size of 4.75 mm was utilized. Tests were carried out according to the ASTM C127 standard [27] to measure the water absorption of the sand, obtaining the water absorption to be 3.2%. Also, the density of the sand was obtained to be 2510 kg/m^3. Cement type II manufactured by Abyek Cement Company was used for mortar fabrication. Fig. 1 demonstrates the aggregate grading curve.

The properties of the polypropylene-type fiber are shown in Table 1. Fiber total volume content in making mortar is in a volume fraction of 0.3%.

In the “Pull-off” method, a two-component epoxy resin adhesive composition (mixed in a volume ratio of 1 to 1) was used to bond steel cylinders to the mortar surface. The shear strength, compressive strength, and Young’s modulus of the adhesive are 15, 70, and 12750 MPa, respectively. The ratios used in making cement mortar are shown in Table 2.

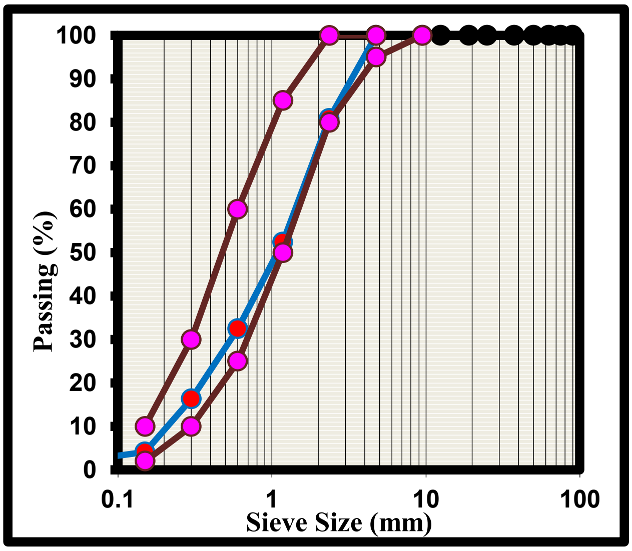


Fig. 1. Sand gradation chart.

Table 2. Mortar mixing design.

Type of mortar	Sand	Cement	Water	Fiber
M1	1320	660	264	2.7
M2	1232	616	308	2.7


a) Adhesive

b) Polypropylene fibers

Fig. 2. The fibers and adhesive.

Table 3. The number of specimens.

Type of test	Compressive Strength	Flexural Strength	“Pull-off”	“Friction-Transfer”
Number of samples	120 Pieces	60 Pieces	40 Pieces	40 Pieces

Fig. 2 shows the polypropylene fibers and two-part epoxy adhesive.

2- 2- Making the Samples

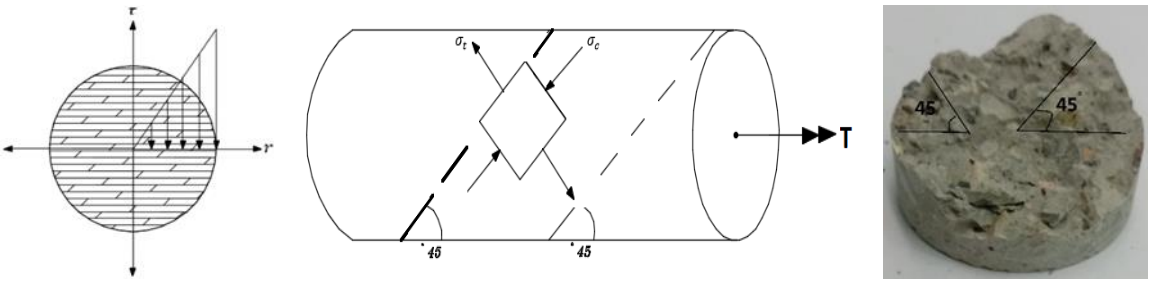
The cement mortars with the abovementioned ratios were made in two forms of mortars without fiber and with polypropylene, placed in the mold for 24 h, and then removed and placed in water in the curing practice. Samples were examined at the ages of 3, 7, 28, 42, and 90 days by “friction transfer”, “Pull-off”, “compressive and flexural” tests. Table 3 shows the number of specimens made for each test.

2- 3- Experimental Methods

The compressive and flexural strengths of cement mortars of different ages were evaluated in the “friction transfer” test. To this end, a core with a 50-mm diameter and 25-mm height was first created on the surface of the test site by a core drilling machine. Then, the metal device for the “friction

a) "Friction transfer" device and Torque **b) Stabilization of device on core**

Fig. 3. “Friction Transfer” test.



a) Maximum shear stress **b) Angle of failure perpendicular to the tensile stress** **c) Core failure**

Fig. 4. Theory of “Friction Transfer” method.

transfer” test was placed on the core and a twisting moment was placed on the mentioned device using an ordinary torque wrench to create a failure to the partial core (see Fig. 3).

In the “friction transfer” test, the broken core is cylindrical with a circular cross-section. When the torque wrench inserts a twisting moment into the core, maximum shear stresses are created on the cylinder and at the furthest distance from the center of the core. Fig. 4a illustrates the maximum shear stresses that occur in the core. Using the Mohr’s Circle theorem, Fig. 4b illustrates that the maximum tensile, compressive, and shear stresses are three times as much as the radius of the Mohr’s circle. In this case, the main tensile and compressive stresses are at a 45-degree angle, and since the brittle materials, such as concrete, have a tensile failure, failure sheets are perpendicular to the tensile stresses and core failure has a failure angle of about 45 degrees in the “friction transfer” test (see Fig. 4c).

In this case, the stress created by the twisting effect on the core surface is calculated as Eq. (1)28]].

$$\tau_{E-\max} = \frac{Tr}{J}, J = \frac{\pi r^4}{2} \rightarrow \tau_{E-\max} = \frac{2T}{\pi r^3} \quad (1)$$

Where r is the radius of the partial core and J is the polar moment of inertia.

An average of six standard 50-mm cubic samples was used to measure the compressive strength of mortars based on the ASTM C109 standard [29]. Before testing, the surfaces of the samples should be cleaned and dried, and loose aggregates and particles stuck to them should be removed. The load should be applied to smooth sides of the specimen that have been in contact with the mold body. The loading rate for testing the mortar sample is 41 MPa/min, which means 1710 N/s. Fig. 5(a) shows the mortar compressive strength test apparatus. The compressive strength of the mortar is determined by dividing the force applied to the cross-sectional area of the mortar specimen.

To measure the flexural strength of mortar, prismatic samples with dimensions of 40×40×160 mm were also made and tested according to the ASTM C348 standard [30]. The prismatic specimens are dried, and the loose aggregates and particles stuck to the specimen surfaces, which come in contact with the supports and load points, are removed. The load is applied at the rate of 2.67 KN/min. The maximum load specified by the machine is recorded, and the flexural strength of the sample is determined as Eq. (2).

a) Flexural test device **b) Compressive test device**

Fig. 5. Test Devices.

a) Test method **b) Test result**

Fig. 6. The Pull-off test.

$$S_f = 2.8P \tag{2}$$

Where S_f is the flexural strength (KPa), and P is the maximum load applied (N).

Fig. 5 shows the flexural and compressive strength test device for mortar samples.

The "Pull-off" test was also used to evaluate the compressive and flexural strengths of mortars. In this test, a 50-mm diameter steel cylinder is bonded to the surface of the test site and then the cylinder is pulled to be separated from the mortar surface. In Fig. 6, the "Pull-off" test procedure and the test result can be observed.

In the following, the degree of correlation between the results of "Pull-off" and Friction-Transfer in-situ tests with the results obtained from compressive and flexural strength laboratory tests is determined. Then, by presenting the calibration diagrams, the amount of compressive and flexural strength of the mortars reinforced with polypropylene fibers can be estimated using the results of in-situ tests.

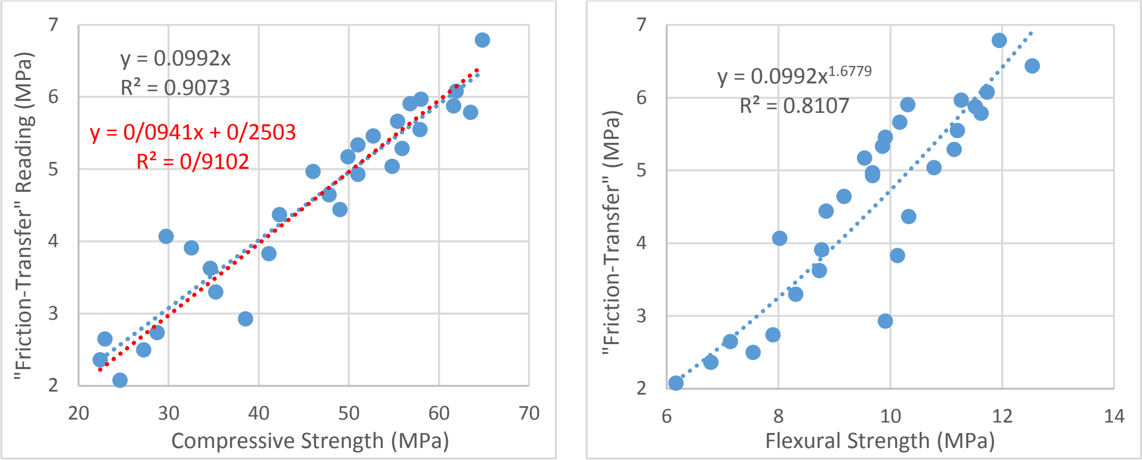
3- Results and Analysis

3- 1- Results of the "Friction Transfer" Test

Using the regression analysis, the correlation between the readings of the "friction transfer" test and the compressive and flexural strengths of cement mortars with and without fibers was presented in this section. First, the coefficient of determination and correlation coefficient between the results of the "friction transfer" test and the compressive strength of mortars were determined using linear regression. Then, the coefficient of determination was calculated based on the research hypothesis indicating that the regression line should first cross the coordinate axis and its calibration equation should be y = ax, followed by performing the regression analysis. Finally, power regression analysis would be used if there was a difference between the coefficients of determination in the two cases. Since the relationship between compressive and flexural strengths is usually expressed as power regression, the present study tried to use power regression analysis to calculate the correlation coefficients and the coefficients of determination between "friction transfer" and flexural strength tests.

Table 4. “Friction-Transfer” and “Pull-off” Results.

Type of Test	Mortar	3 Days	7 Days	28 Days	42 Days	90 Days
“Pull-off”	M1	1.48	2.17	2.71	3.37	3.72
	M2	1.31	1.87	2.42	2.9	3.26
“Friction-Transfer”	M1	3.03	4.65	5.62	6.28	6.71
	M2	2.7	4.02	4.98	5.56	5.91



a) Friction transfer- compressive strength **b) Friction transfer- flexural strength**

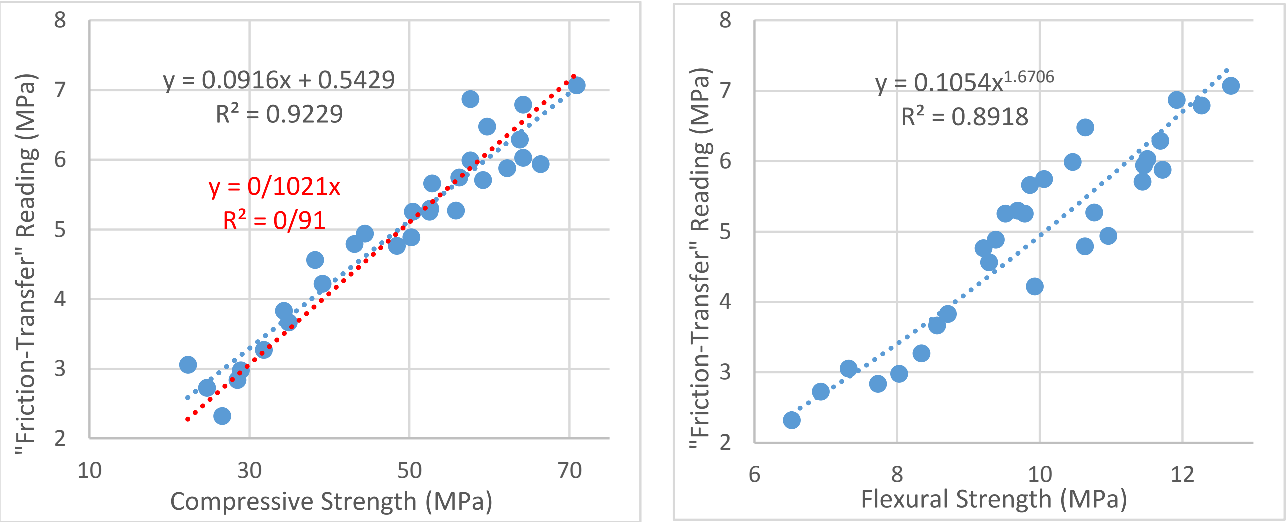
Fig. 7. Correlation between “friction transfer” test and mechanical properties of cement mortars without fiber.

In the calibration diagrams presented below, the horizontal axis is related to the results of compressive strength and flexural strength of repair mortars. In these diagrams, the vertical axis is related to the results achieved from the “Pull-off” and Friction-Transfer tests. In the “Pull-off” test, the maximum tensile force was determined by the device. Then by dividing the tensile force to the cross-sectional area of the 50 mm cube sample, the results obtained were presented in terms of MPa. Also, in the Friction-Transfer test, the amount of torsional moment applied to the core was measured by a torque meter. Then, using Eq. (1), the results gained were expressed in terms of MPa. Since the diameter of the steel cylinder and the concrete core used in the above tests are constant, so the tensile force or torsional moment can be used directly in the results. However, in this study, to align the horizontal and vertical axes in the calibration diagrams, all the results are presented in terms of MPa.

Table 4 shows the results accomplished from applying the “Pull-off” and Friction-Transfer tests on fiber-reinforced mortars. As can be seen in Table 4, the results obtained from the “Pull-off” and Friction-Transfer tests have increased over time due to the completion of the hydration process in the mortar and the increase of its strength. The records achieved from the above tests at the age of 90 days compared to the age of 3 days for M1 mortar are 151 and 122%, respectively. The same data for M2 mortar are 149 and 118%, respectively. Also, by comparing different mortars, it can be observed that the results obtained from M1 are higher than M2 mortar, which is due to the low water-cement ratio in M1 mortar. Therefore, this has led to a further increase in the strength and, thus, to a rise in the records attained from the “Pull-off” and Friction-Transfer tests.

Fig. 7 illustrates the relationship between compressive and flexural strengths of both cement mortars, and the results of the “friction transfer” test for fiberless mortars.

Fig. 7a shows the comparison between the results of the “friction transfer” test and the compressive strength of mortars, indicating that the coefficient of determination and the correlation coefficient are respectively 0.91% and 0.95% by performing the linear regression. However, if the linear regression equation is chosen as y = ax and correlation analysis is performed again, the coefficient of determination will be calculated as 0.907, which has been obtained due to little difference between the coefficients of determination; therefore, the compressive strength of the cement mortar can be measured by the “friction transfer” test, the results of



a) Friction transfer- compressive strength

b) Friction transfer- flexural strength

Fig. 8. Correlation between "friction transfer" test and mechanical properties of cement mortars with fiber polypropylene.

which was obtained through the linear calibration curve by at a confidence interval of 95% (see Fig. 7a).

Fig. 7b also illustrates that the correlation coefficient and the coefficient of determination between the results of the "friction transfer" test and flexural strength of cement mortar were 90% and 81%, respectively. Therefore, the flexural strength of repair mortars can be measured using the "friction transfer" test, the results of which were obtained through the power calibration curve by at a confidence interval of 90% (see Fig. 7b).

Fig. 8 illustrates the relationship between compressive and flexural strengths of both cement mortars, and the results of the "friction transfer" test for fiber-reinforced mortars.

Fig. 8a shows the comparison between the results of the "friction transfer" test and the compressive strength of fiber-reinforced mortars, indicating that the coefficient of determination and the correlation coefficient are respectively 0.92% and 0.95% by performing the linear regression. However, if the linear regression equation is chosen as y = ax and correlation analysis is performed again, the coefficient of determination will be calculated as 0.91, which has been obtained due to little difference between the coefficients of determination; therefore, the compressive strength of the fiber-reinforced mortar can be measured by the "friction transfer" test, the results of which was obtained through the linear calibration curve by at a confidence interval of 96% (see Fig. 8a).

Fig. 8b also illustrates that the correlation coefficient and the coefficient of determination between the results of the "friction transfer" test and flexural strength of fiber-reinforced mortar were 94% and 89%, respectively. Therefore, the flexural strength of fiber-reinforced mortars can be measured using the "friction transfer" test, the results of which were obtained through the power calibration curve by at a confidence interval of 95% (see Fig. 8b).

A comparison of Figs. 7 and 8 indicates that there is a larger correlation coefficient between the friction-transfer results and compressive strengths than that between the friction-transfer results and flexural strengths. As a result, higher dispersion of points is observed in Figs. 7b and 8b. The ASTM C109 Standard mentions that the standard deviation of the compressive strength results of specimens should not exceed 5%. However, the ASTM C348 Standard allows for a standard deviation of up to 10% for the flexural strength results of specimens. For this reason, the dispersion of points is lower in Figs. 7a and 8a than in Figs. 7b and 8b.

Fig. 9 illustrates the friction-transfer results at different ages to evaluate the effects of fibers. As can be seen in Fig. 9, the addition of fibers enhanced the friction-transfer results by 8.48% on average. At the end of the paper, the reasons for the enhanced results of fiber-reinforced mortars are discussed by modeling the test in ABAQUS and studying the failures and cracks.

3- 2- Results of the "Pull-off" Test

Fig. 10 illustrates the relationship between compressive strength and flexural strength of both cement mortars, and the results of the "Pull-off" test for fiberless mortars.

Fig. 10a shows the comparison between the results of the "Pull-off" test and the compressive strength of mortars, indicating that the coefficient of determination and the correlation coefficient are respectively 0.915% and 0.95%

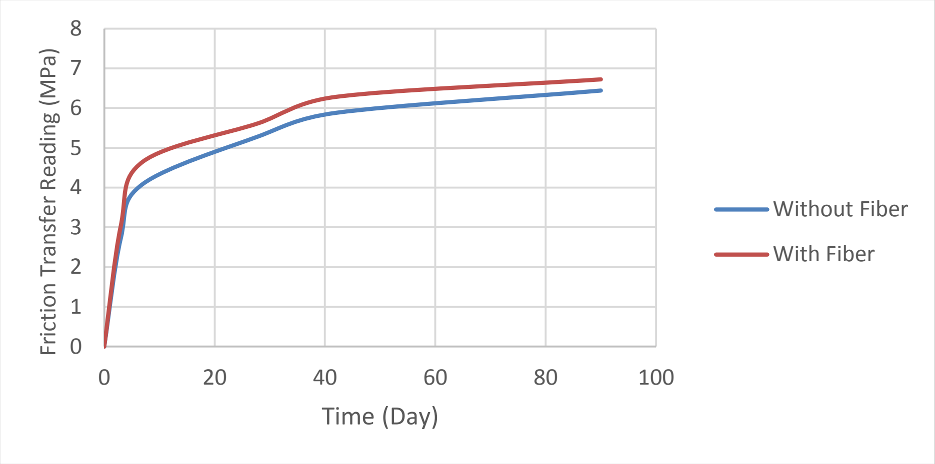
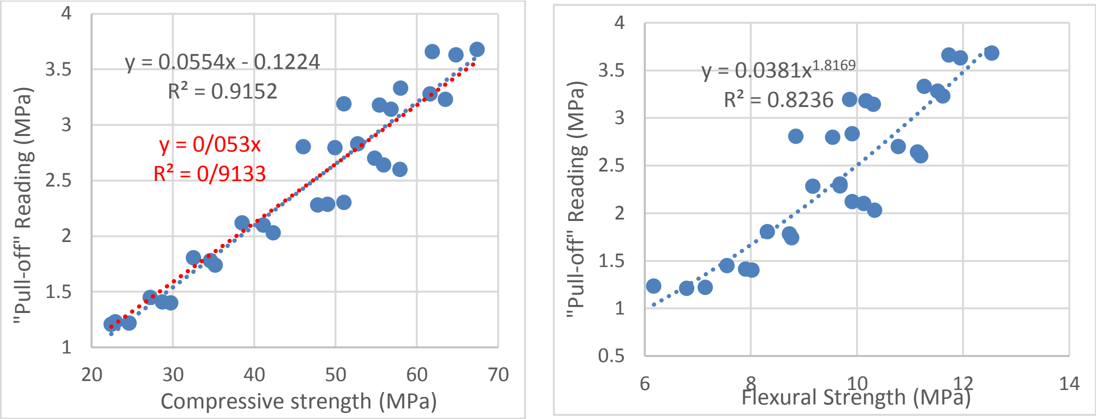


Fig. 9. The friction-transfer results of fiber-reinforced and fiberless specimens.



a) "Pull-off"- compressive strength

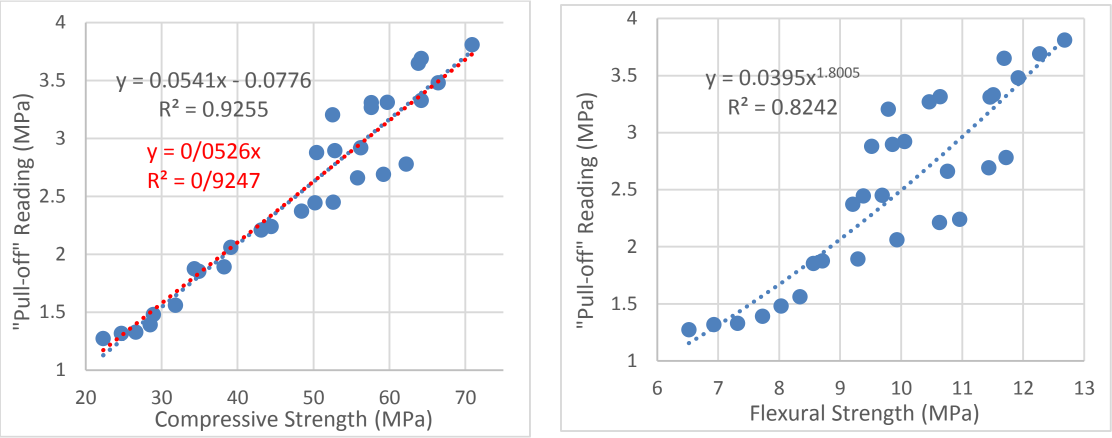
b) "Pull-off"- flexural strength

Fig. 10. Correlation between "Pull-off" test and mechanical properties of cement mortars without fiber.

by performing the linear regression. However, if the linear regression equation is chosen as y = ax and correlation analysis is performed again, the coefficient of determination will be calculated as 0.913, which has been obtained due to little difference between the coefficients of determination; therefore, the compressive strength of the cement mortar can be measured by the "Pull-off" test, the results of which was obtained through the linear calibration curve by at a confidence interval of 95% (see Fig. 10a). Fig. 10b also illustrated that the correlation coefficient and the coefficient of determination between the results of the "Pull-off" test and flexural strength of cement mortar were 91% and 82%, respectively. Therefore, the flexural strength of repair mortars can be measured by using the "Pull-off" test; the results of the mentioned test through the power calibration curve obtained by in the confidence interval of 91% (see Fig. 10b).

Fig. 11 illustrates the relationship between compressive strength and flexural strength of both cement mortars, and the results of the "Pull-off" test for fiber-reinforced mortars.

According to Fig. 11a, linear regression showed that the coefficient of determination between the results of the "Pull-off" test and flexural strength of cement mortar with polypropylene fiber was 0.925 and the coefficient correlation was 0.961; however, if the linear regression equation is chosen as y = ax and correlation analysis is performed again, the coefficient of determination will be calculated as 0.924 which has been obtained due to little difference between the coefficients of determination; therefore, the compressive strength of the cement mortar with polypropylene fiber can be measured by using "Pull-off" test; the results of the mentioned test through the linear calibration curve obtained by in the confidence interval of 96% (see Fig. 11a).



a) “Pull-off”- compressive strength **b) “Pull-off”- flexural strength**

Fig. 11. Correlation between “Pull-off” test and mechanical properties of cement mortars with fiber polypropylene.

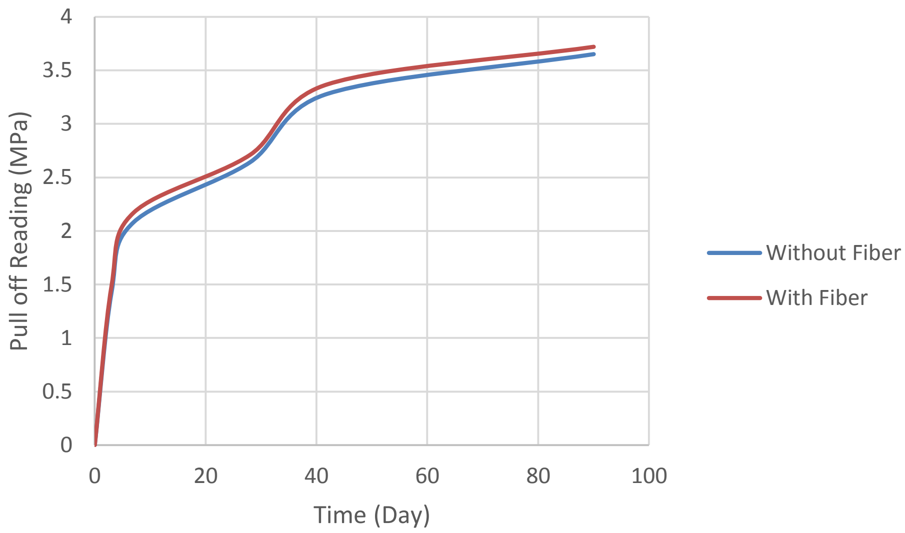


Fig. 12. The “Pull-off” results of fiber-reinforced and fiberless specimens.

Fig. 11b illustrated that the correlation coefficient and the coefficient of determination between the results of the “Pull-off” test and flexural strength of cement mortar with polypropylene fiber were 0.907 and 0.824, respectively. Therefore, the flexural strength of repair mortars with polypropylene fibers can be measured by using the “Pull-off” test; the results of the mentioned test through the power calibration curve obtained by in the confidence interval of 91% (see Fig. 11b).

It should be noted that the failure of both methods is very partial. Unlike the “pull-off” test, which uses chemical adhesives to bond the steel cylinder to the mortar surface, the “friction transfer” test used the devices which were all mechanical; therefore, they had a unique performance in any experimental and environmental conditions. It can also be used without any humidity or temperature limitations.

A comparison of Figs. 10 and 11 indicates that there is a larger correlation coefficient between the “Pull-off” results and compressive strengths than that between the “Pull-off” results and flexural strengths. As a result, higher dispersion of points is observed in Figs. 10b and 11b. The ASTM C109 Standard mentions that the standard deviation of the compressive strength results of specimens should not exceed 5%. However, the ASTM C348 Standard allows for a standard deviation of up to 10% for the flexural strength results of specimens. For this reason, the dispersion of points is lower in Figs. 10a and 11a than in Figs. 10b and 11b.

Fig. 12 illustrates the “Pull-off” results at different ages to evaluate the effects of fibers. As can be seen in Fig. 12, the addition of fibers enhanced the “Pull-off” results by 3.2% on average. At the end of the paper, the reasons for the enhanced results of fiber-reinforced mortars are discussed by modeling

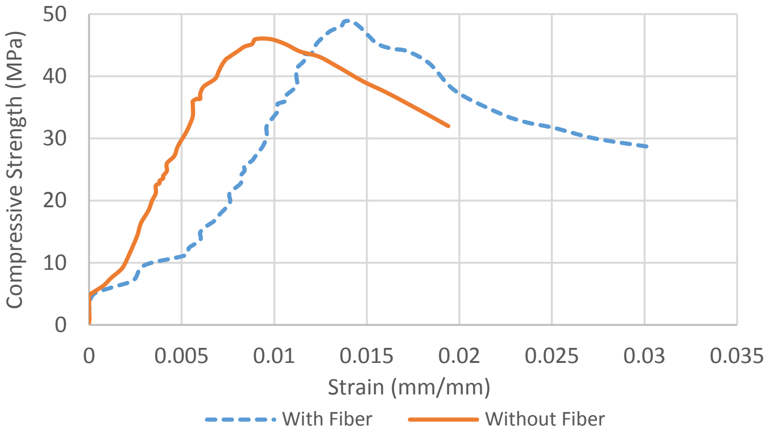


Fig. 13. Compressive behavior of mortars with and without fibers.

Table 5. Compressive strength of cement mortars (MPa).

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

the test in ABAQUS and studying the failures and cracks.

A comparison of the “Pull-off” results to the friction-transfer results suggests that fibers had a larger effect on the friction-transfer results since the friction-transfer test is performed by coring within the object, while the “Pull-off” test involves only surface contact with the object. For this reason, fibers have smaller effects on the “Pull-off” test.

3- 3- The effect of fibers on compressive and flexural strength of cement mortars

A certain amount of fibers increases the toughness of the materials against the stresses by delaying cracking as well as transferring the stresses along the width of the cracks, which enables the mortars to bear much larger deformations at peak stresses. Fig. 13 illustrates the compressive behavior of two mortar samples without fibers and with polypropylene fibers.

Fig. 13 illustrates that the toughness of the samples with fibers increased under the pressure. The maximum stress tolerated by the fiberless sample is 46 MPa at a strain of 0.0098 while the failure of the sample with polypropylene fibers occurs at a stress of 48.8 MPa and a strain of 0.0142. It can be observed that the maximum deformation, which a fiberless sample can bear, is about 45% less than that of the fiber-containing sample. In another study, the effect of polypropylene fibers on the crack formation in mortars indicated that adding polypropylene fibers caused a delay in the propagation of cracks in the mortar and prevented their opening [5].

As can be seen in Fig. 13, the fiber-reinforced mortar had softer and more ductile behavior than the non-reinforced mortar at both the beginning and end of loading. In non-reinforced mortars, due to low ductility, cracks began to grow more rapidly when the compressive load was applied. Also, the non-reinforced mortars failed at lower strains. On the other hand, fiber-reinforced mortars allowed for larger deformations due to postponed cracking and enhanced toughness by transferring the stress along the cracks. As a result, initial cracks and ultimate failure occurred at larger strains. Also, the cracking initialization and ultimate failure of fiber-reinforced and non-reinforced mortars in the ABAQUS models are compared in more detail.

Table 5 illustrates the compressive strength of M1 and M2 cement mortars.

Table 5 shows that adding a fiber volume fraction of 0.3% improves the compressive strength of mortars at different ages. Adding polypropylene fibers to M1 mortar increased the compressive strength of mortars by 3.7% on average. By adding fibers, the compressive strength of M2 mortars increased by 8.4 on average. It is also observed that M1 mortar has higher compressive strength than M2 mortar due to its

Table 6. Illustrated the flexural strength of M1 and M2 cement mortars.

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

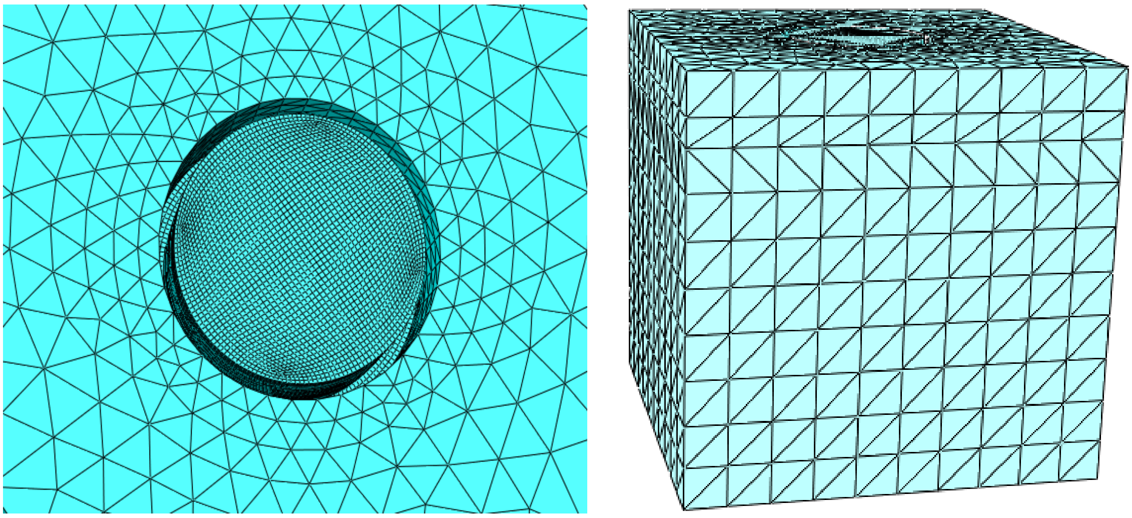


Fig. 14. The meshes in the sample in the "Friction Transfer" test.

lower water-cement ratio in M1 mortar. Table 6 showed that adding a fiber volume fraction of 0.3% improves the flexural strength of mortars at different ages. Adding polypropylene fibers to M1 mortar increased the flexural strength of mortars by 3.7% on average. By adding fibers, the flexural strength of M2 mortars has increased by 2.1% on average.

In another study, the effect of polypropylene fibers on the mortars concluded that these fibers could improve the compressive and flexural strengths of mortars [6].

3- 4- Finite Element Method to Evaluate Mortar Behavior in "Pull-off" and "Friction Transfer" Tests

Brittle cracking smeared cracking and concrete damage plasticity models can be used to model the nonlinear behavior of brittle materials in ABAQUS software. The concrete damage plasticity model, which has mechanisms of tensile cracking and compressive crushing strength, can be used in static and dynamic analyses. After introducing the materials and stress-strain curves and the required values from the module property section and the creative material section, one of the important issues which should be considered is meshed convergence. The solutions to a finite element problem always depend on the size of the meshes and elements. The numerical solution of the problem converges to a single solution by increasing the mesh density, reducing the dimensions of the elements, and thus reducing the volume element. However, the finer mesh increases the power of the hardware in solving the finite element model resulting in spending more processing time. Mesh convergence has occurred if the results significantly changed by constantly decreasing the size of elements.

To study the behavior of the samples in "friction transfer" and "Pull-off" tests, the cubic piece of mortar meshed in the form of the combination of the C3D8R and C3D4 elements. In both modelings, the main section which was affected by tension or compression had an 8-node cubic element with reduced integration (C3D8R). To obtain the appropriate size of the elements in this modeling, responses were converged with elements between 2, 1, and 0.5 mm; however, a 1 mm element was selected in this study The lateral sections have also meshed with a 4-node tetrahedral element type with a minimum size of 1 mm element in the areas connected to the main elements and a maximum size of 15 mm element at the edges.

Fig. 14 illustrated meshes in a cubic sample in the "friction transfer" test. In this section, the important points should be summarized and revised to easily inform the reader about the main results. The contribution of the article should be clearly stated in the conclusion section and the sentences should not be identical to those used in the abstract. In this part, the

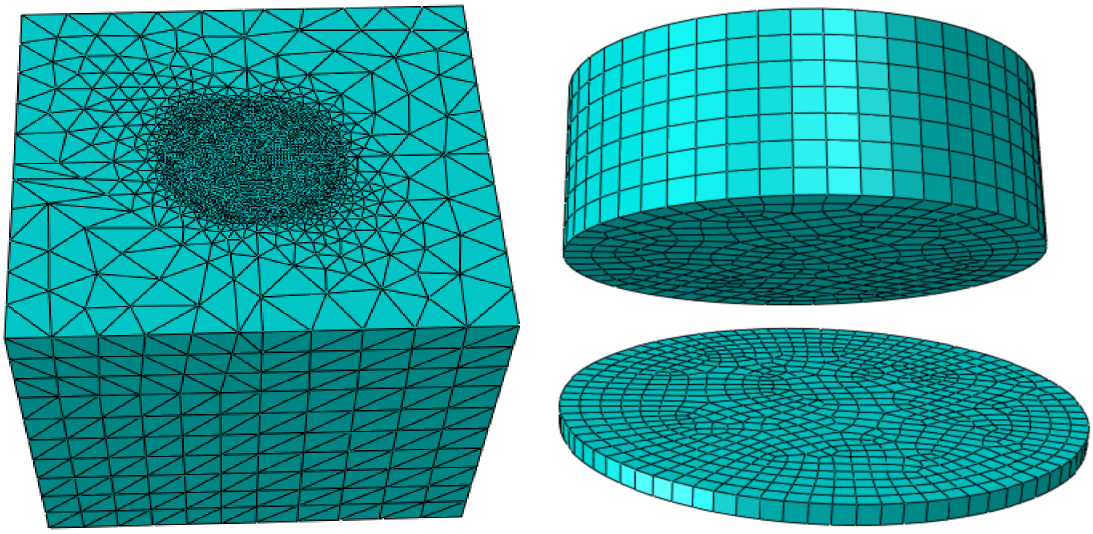


Fig. 15. The meshes in the sample in the "Pull-off" test.

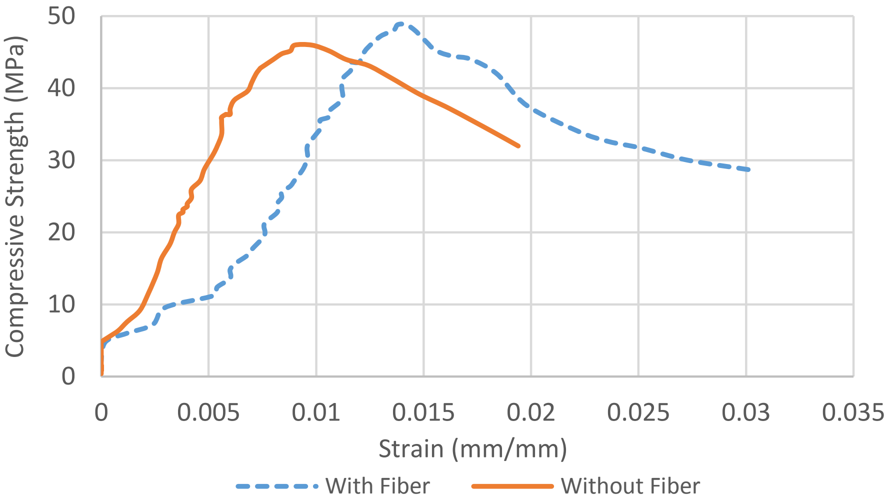


Fig. 16. The nonlinear behavior curves of the mortars introduced to ABAQUS.

applications of the research conducted can be pointed out and new vague points that demand further research can be proposed or the development of the subject in other areas can be suggested.

Also, the 2-mm C3D8R type element adhesive piece and the 2-mm element steel piece meshed in the "Pull-off" test. Along the axis, the elements were 1 mm for the steel piece (Fig. 15).

To compare the results of the laboratory with those of finite element modeling, the mortar samples were modeled in two cases including a fiberless mortar sample with a compressive strength of 47.6 MPa and a fiber-containing mortar sample with a compressive strength of 50.4 MPa.

Fig. 16 demonstrates the nonlinear behavior of the fiber-reinforced and fiberless mortars for modeling the tests.

Stiffness recovery is an important aspect of the mechanical responses of cementitious materials under loading. The experimental results of quasi-brittle materials have mostly exhibited improved compressive stiffness due to crack closing during changing the load from tensile into compressive. On the other hand, the tensile stiffness is not recovered during changing the load from compressive into tensile after the formation of micro-cracks in the concrete smashing condition. This behavior, which arises from $w_t=0$

Table 7. The plasticity properties of the mortar.

Viscosity	K	σ_{b0}/σ_{c0}	ε	ψ
0	0.667	1.16	0.1	36

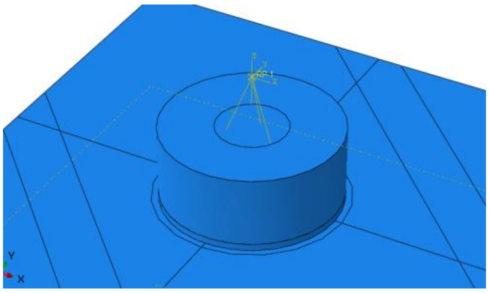
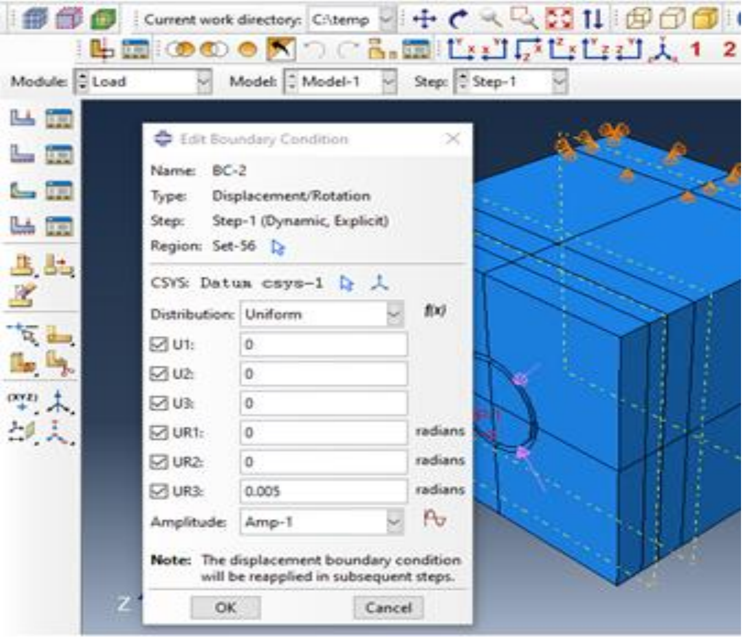


Fig. 17. Reference point definition for the 'Pull-off" test.



Edit Boundary Condition

Name: BC-2
Type: Displacement/Rotation
Step: Step-1 (Dynamic, Explicit)
Region: Set-56
CSYS: Datum csys-1
Distribution: Uniform f(x)
☑ U1: 0
☑ U2: 0
☑ U3: 0
☑ UR1: 0 radians
☑ UR2: 0 radians
☑ UR3: 0.005 radians
Amplitude: Amp-1

Note: The displacement boundary condition will be reapplied in subsequent steps.

OK Cancel

Fig. 18. Apply torque in the "friction transfer" test.

and w_c=1, is default to the program. To define the behavior of the concrete after cracking under tensile loading, the compressive stiffening coefficient w_c was selected to be 1 as default so compressive stiffening would be recovered during crack closing (after cracking under tensile loading). On the contrary, w_t was considered as 0 to ignore tensile stiffening recovery. Also, the default plasticity values were applied, as shown in Table 7.

To model the "Pull-off" test, a reference point above the screw location of the steel cylinder was defined using "Create Reference Point" in the module of "Interaction." Then, the reference point was joined to the cylinder by using the command "Coupling" so the tensile load is applied through the point, as shown in Fig. 17.

In the "Friction-Transfer" test, a torsional moment was applied in the form of rotational movement around the core axis to the core circumference by using "Coupling" (Fig. 18).

In the laboratory, the final twisting moments were respectively 115 Nm and 120 Nm for the core failure without and with fiber in the "friction transfer" test. In the FE analysis, the ultimate moment, which caused the concrete core to fail, was obtained to be 104.3 N/m. The ultimate moment was found to be 114 N/m for the fiber-reinforced model. The critical load of the fiberless model occurred at a rotation of 0.0044 rad. The addition of fibers enhanced the strain of the mortar, with the ultimate failure occurring at 0.025 rad, as shown in Fig. 19.

In the modeling of the sample in the "friction transfer" test, twisting torque was applied using coupling around the axis and the core environment. The initial cracks were 27.32

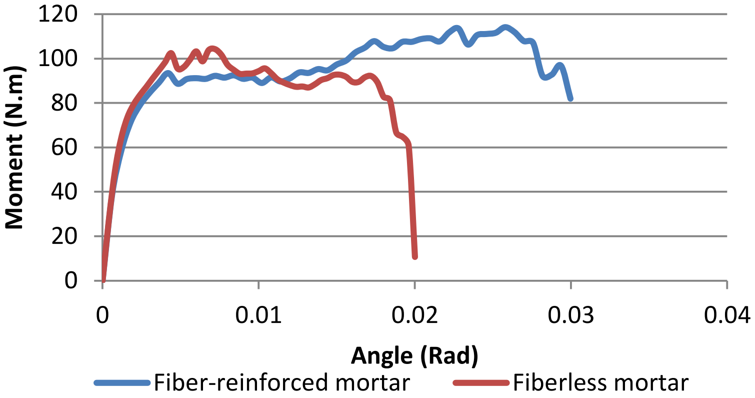
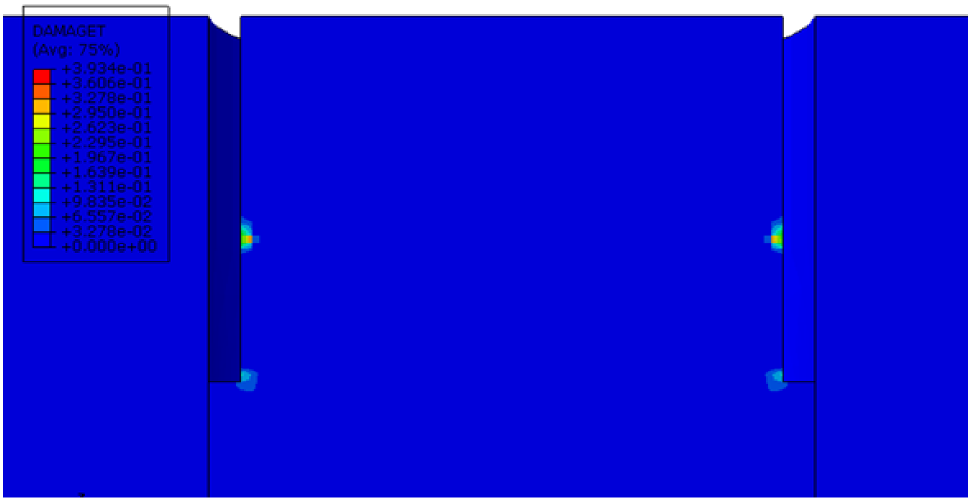
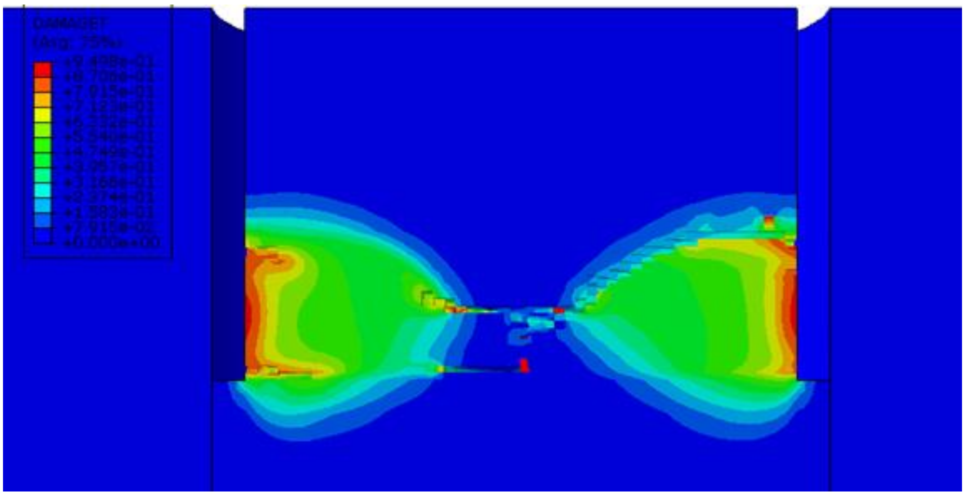


Fig. 19. A comparison of fiber-reinforced and fiberless specimens in the friction-transfer test.



a) Crack initiation at the edges



b) The moment of core failure

Fig. 20. Crack initiation and moment of core failure in the “friction transfer” test.

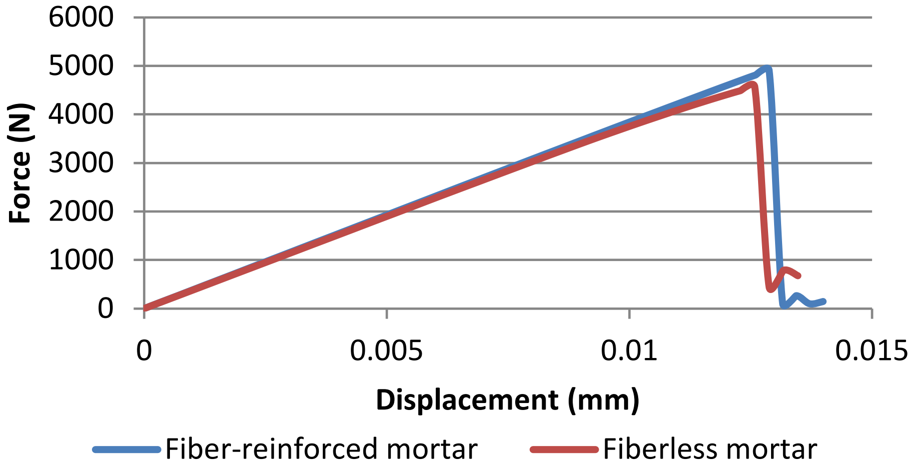


Fig. 21. A comparison of fiber-reinforced and fiberless specimens in the 'Pull-off' test.

Nm at the edges of the sample without fiber and started from the corners that were under the most torque. Also, the first cracks in the sample with fiber started at 38 Nm.

Then, in the fiberless sample, the torque increased with increasing rotational speed until it reached 102 Nm. At this moment, the cracks reach each other leading to the initial damage. Since then, the velocity of damages increased due to the reductions of cross-section and core strength, and finally, complete failure occurs at 104 Nm in the ordinary mortar. However, the fiber-reinforced mortar still bears the force and then fails by increasing torque to 114 Nm. It can be observed that the results of the "friction transfer" test in the laboratory are highly consistent with those of the modeling. Fig. 20 illustrates the moment of crack initiation and core failure in the "friction transfer" test.

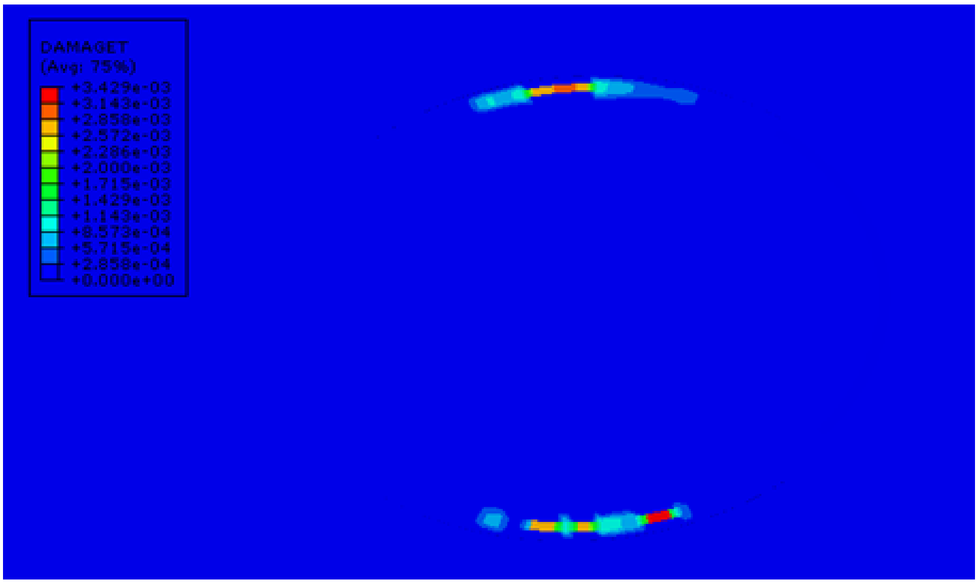
In the "Pull-off" test the laboratory results showed that the sample without fiber failed at 4500 N. while, the sample with fiber failed at 4750 N. According to Fig. 21, the load applied by the reinforced specimen to fibers was obtained to be 4905 N, while the load of the common mortar was derived to be 4567 N. As can be seen, there is a high agreement between the FEM and experimental results.

In the modeling mode of the "Pull-off" test, the cracks appeared at 2248 N in the ordinary mortar sample whereas the initial cracks occurred at 2701 N in the sample with fiber. The increase in force is linear and final failure occurred at 4555 N in the ordinary mortar sample while it occurred at 4905 N in the sample with fiber. It is observed that the results of finite element modeling are highly consistent with the results of the "Pull-off" test in the laboratory. Fig. 22 illustrated an example of crack initiation and maximum stresses under the steel cylinder in the "Pull-off" test.

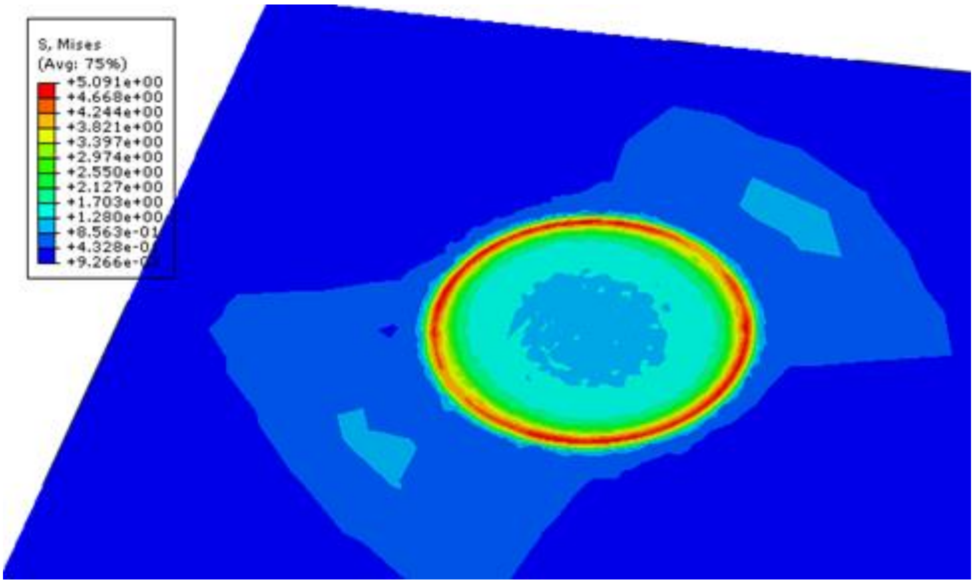
4- Conclusion

Considering the awareness of the strengthening procedure of common and fiber-reinforced cementitious mortars mostly utilized as repair layers for reinforced concrete structures, the present study introduced the semi-destructive in-situ "friction-transfer" test and evaluated the correlation between the in-situ and experimental results. Then, calibration diagrams were plotted to translate the in-situ results into the compressive and flexural strengths of the fiber-reinforced mortars. Finally, the effects of fibers on the results were evaluated by FEM in ABAQUS, comparing the numerical and experimental results. The results are provided in the following.

- Given the high correlation between the readings of the "Friction-Transfer" and "Pull-off" tests and the compressive and flexural strengths of ordinary and fiber-reinforced mortars, it is easy to evaluate the strength of the mortar in these tests.
- Given the mechanical devices used in this test, the damage caused by the "Friction-Transfer" test is very partial, has unique performance for any experimental and environmental conditions, and is usable without humidity or temperature limitations.
- The results of numerical modeling showed the improved behavior of fiber-reinforced mortars and increased toughness of mortar by delaying the crack initiation and bearing further deformation at peak stresses.
- The results showed that the experimental readings were highly consistent with the results of numerical modeling of "Friction-Transfer" and "Pull-off" methods using the ABAQUS software.
- Adding polypropylene fiber at a volume fraction of 0.3% increased the compressive and flexural strengths of cement mortars by 4.2% and 2.2%, respectively.



a) Crack initiation



b) Maximum stress under the cylinder

Fig. 22. Crack initiation and maximum stresses in the "Pull-off" test.

Reference

[1] S. Alsadey, and M. Salem, Influence of Polypropylene Fiber on Strength of Concrete. American Journal of Engineering Research, 5(7) (2016) 223-226.

[2] M. Alam, I. Ahmad, and F. Rehman, Experimental Study on Properties of Glass Fiber Reinforced Concrete, International Journal of Engineering Trends and Technology 24(6) (2015) 297-301.

[3] ACI Committee 544, State-of-the-Art Report on Fiber Reinforced Concrete, Concr. Int., ACI Manual of Concrete Practice, Part 5, Report 544.1R-96 (2009).

[4] A.S. Shakir, and M.E. AL-Azaawee, Effect of Polypropylene Fibers on Properties of Mortar Containing Crushed Brick as Aggregate. Journal of engineering and technology 26(12) (2008) 1508-1513.

[5] H.A. Mesbah, and U.F. Buyle-Bodin, Efficiency of polypropylene and metallic fibers on control of shrinkage and cracking of recycled aggregate mortars. Construction and Building Materials 13 (1999) 439-447.

[6] A. Sadrmomtazi, and A. Fasihi, Influence of polypropylene fibers on the performance of nano-sio2-incorporated mortar. Iranian Journal of Science & Technology, Transaction B: Engineering 34 (2010) 385-395.

[7] R. A. S. Mohamed, Effect of polypropylene fibers on the mechanical properties of normal concrete. Journal of Engineering Sciences, Assiut University 34 (2006) 1049-1059.

[8] D. S.Dharan, and A. Lai, Study the effect of polypropylene fiber in concrete. International Research Journal of Engineering and Technology 3(6) (2016) 616-619.

[9] V. S. Vairagade, K. S. Kene, and N. V. Deshpande, Investigation on compressive and tensile behavior of fibrillated polypropylene fibers reinforced concrete. International Journal of Engineering Research and Applications 2(3) (2012) 1111-1115.

[10] M. Santandrea, I. A. O. Imohamed, H. Jahangir, C. Carloni, C. Mazzotti, S. De Miranda, and P. Casadei, An investigation of the debonding mechanism in steel FRP- and FRCM-concrete joints. In 4th Workshop on the new boundaries of structural concrete (2016) 289-298.

[11] M. Bagheri, A. Chahkandi, and H. Jahangir, Seismic Reliability Analysis of RC Frames Rehabilitated by Glass Fiber-Reinforced Polymers. International Journal of Civil Engineering, 17(11) (2019) 1785-1797.

[12] H. Jahangir, and M. R. Esfahani, Investigating loading rate and fiber densities influence on SRG-concrete bond behavior. Steel and Composite Structures, 34(6) (2020) 877-889.

[13] ASTM C42 / C42M-18a, Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete. ASTM International, West Conshohocken, PA, (2018).

[14] A. Masi A. Digrisolo, and G. Santarsieo, Experimental evaluation of drilling damage on the strength of cores extracted from RC buildings. Proceedings of World Academy of Science, Engineering and Technology 7(7) (2013) 749.

[15] ASTM C900-15, Standard Test Method for Pullout Strength of Hardened Concrete. ASTM International, West Conshohocken, PA, (2015).

[16] ASTM C597-16, Standard Test Method for Pulse Velocity through Concrete, ASTM International, West Conshohocken, PA, (2016).

[17] ASTM C805/C805M-18, Standard Test Method for Rebound Number of Hardened Concrete. ASTM International, West Conshohocken, PA, (2018).

[18] M. Naderi, Assessing the Insitu Strength of Concrete, Using new Twist-off Method. International Journal of Civil Engineering 4(2) (2006) 146-155.

[19] M. Naderi, Adhesion of different concrete repair systems exposed to different environments. The Journal of Adhesion 84(1) (2008) 78–104.

[20] M. Naderi, New Method for Nondestructive Evaluation of Concrete Strength. Australian Journal of Basic and Applied Sciences 7(2) (2013) 438-447, 2013.

[21] M. Naderi, and R. Shibani, New Method for Nondestructive Evaluation of Concrete Strength. Australian Journal of Basic Applied Sciences 7(2) (2013) 438-447.

[22] M. Naderi, Friction-Transfer Test for the Assessment of in-situ Strength & Adhesion of Cementitious Materials. Construction & Building Materials 19(6) (2005) 454-459.

[23] M. Naderi, An alternative method for in situ determination of rock strength. Canadian Geotechnical Journal 48 (2011) 1901-1905.

[24] M. Naderi, Evaluating in situ shear strength of bituminous pavements. In Proceedings of the institution of Civil Engineering, (2006) 61-65.

[25] M. Naderi, O. Ghodousian, Adhesion of Self-Compacting Overlays Applied to Different Concrete Substrates and Its Prediction by Fuzzy Logic, The Journal of Adhesion 88(10) (2012) 848-865.

[26] M. Naderi, Effects of Cyclic Loading, Freeze-Thaw and Temperature Changes on Shear Bond Strengths of Different Concrete Repair Systems. The Journal of Adhesion 84(9) (2008) 743-763.

[27] ASTM C127, Standard test method for density, relative density (specific gravity), and absorption of fine aggregate. West Conshohocken PA, American Society for Testing and Materials, (2012).

[28] F. P. Beer, E. R. Johnston, J. T. Dewolf, and D. F. Mazurek, Mechanics of Materials. McGraw-Hill Education; 7th Edition (2014).

[29] ASTM C109, Standard test method for compressive strength of hydraulic cement mortars (using 2-in. or [50-mm] cube specimens), American Society for Testing and Materials, (2013).

[30] ASTM C348-19, Standard test method for Flexural Strength of Hydraulic-Cement Mortars. West Conshohocken PA, American Society for Testing and Materials, (2012).

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