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"Friction-Transfer" Method to Assess the Compressive and Tensile Strengths and Rupture Modulus of Fiber-Reinforced-Pozzolanic Concrete and Mortar/Steel Adhesion

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ABSTRACT: Nowadays, non-destructive tests are of great importance for evaluating the quality of concretes. However, such tests typically measure the relevant parameters indirectly, followed by estimating the strength of the concrete using several equations. Accordingly, the present study utilized the friction transfer method to directly evaluate the compressive and tensile strengths and the rupture modulus of glass and polypropylene fiber reinforced pozzolanic concretes at different ages. The in-situ test results were related to the strength of the fiber-reinforced pozzolanic concrete using linear and power regression analyses. Afterward, calibration curves were plotted to translate the friction transfer results into compressive and tensile strengths and the rupture modulus. To realize this objective, eight mixed designs with compressive strengths of 15-50 MPa were employed. In addition, the effects of the fibers on the adhesion of the mortar and steel were evaluated using the friction transfer test. ABAQUS was employed to model non-reinforced and fiber reinforced concrete specimens and the effects of fibers on the results. The results indicated high correlation coefficients between the experimental tests and friction transfer test results. The addition of fibers led to the improved compressive behavior of the concrete, reduced mortar shrinkage, and increased concrete-steel adhesion.

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1- Introduction

Standard experimental tests only demonstrate the strength of the concrete under specific conditions, and it is possible that the real characteristics and properties of the concrete used in various parts of the structure are not fully represented. The influential factors include failure to consider the curing method and the real conditions of the structure, the way the specimens are selected from among the entire set of specimens, and changes in the type and amount of the materials which might vary from one mold to the other, the difference in compaction rate, and difference in the maintenance temperature of the concrete and its moisture content. Nowadays, there is a tendency to perform in-situ acceptance tests in the form of non-destructive or semi-destructive methods. However, selecting the type of method to use depends on the type of the experiment in terms of its destructiveness, speed of testing, cost, interpretability of the results, and the estimation of the concrete's strength. There are various methods for measuring the in-situ strength of concrete, which are generally classified into three groups, i.e., destructive, semi-destructive, and non-destructive tests. The ultrasonic [1] and Schmidt hammer [2] tests are among the non-destructive tests; however, the presence of pores, cracks, or reinforcement can affect the results. On the other hand, destructive tests include loading the element in the structure or the component as an independent element, coring of a portion of the structure [3], and the pull-out method [4]. It should be noted that these methods have several disadvantages, including great damage to the structure, limited repeatability, high cost, and interference with serviceability during the testing. In addition, the results obtained from testing on cores have shown a lower strength of cores compared to the real compressive strength [5].

One of the semi-destructive methods is the pull-off test [6], and previous studies have shown the suitability of this method for the in-situ assessment of the strength of the concrete [7]. However, one cannot ignore the high price of this apparatus. Another semi-destructive method is the twist-off test. Previous studies have shown that the results of twist-off tests and the compressive strength of concrete specimens made of type II cement exhibit a high correlation coefficient of 93% [8]. Moreover, a correlation coefficient of 94% has been obtained between the results of the twist-off test and the compressive strength of concrete specimens made of type II cement under different curing conditions [9].

Pozzolanic cement can be utilized to prevent the corrosion of concrete in areas that are likely to contain or ions. In addition, pozzolanic cement is employed to produce concrete in hot climates since it generates low heat during the setting time. Shekarchizadeh et al. [10] tested pozzolanic concretes and concluded that it had high corrosion resistance. Gruber et al. [11] found that the diffusivity of ions within

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pozzolanic concrete were lower than that observed within regular concrete. Betis et al. [12] studied pozzolanic mortars and reported that pozzolanic mortars had higher compressive strength and corrosion resistance. Furthermore, [13] investigated the strength and permeability of pozzolanic concrete and observed that pozzolan led to increased strength and reduced permeability of the specimens as compared to regular concrete. In addition, the XRD results and SEM images demonstrated that the microstructures of the pozzolanic specimens were more compact than the non-pozzolanic ones.

Also, the use of nanomaterials in concrete is very common today. Nanomaterials can play a positive role in some concrete properties. The research investigates the effect of activated pozzolan on hydration and the microstructure of high-volume natural pozzolan paste. Thermal activation of natural pozzolan with Ca(OH)2 has been applied with nano-silica as an activator at three different temperatures. X-ray diffraction, thermogravimetric analysis, laser particle analysis, and scanning electron microscopy with energy dispersive spectroscopy were employed. SEM images indicated microstructural improvements of the pastes with activated pozzolans compared to paste with natural pozzolan and natural pozzolan incorporating NS, showing the pore filling effect of activated pozzolans. The microstructural improvements were proportion to the amount of pre-C-S-H formed during the activation of pozzolan [14]. In another study on Nanotechnology: Advantages and drawbacks in the field of construction and building materials, demonstrated that Nanotechnology has the potential to be the key to a brand new world in the field of construction and building materials. Although replication of natural systems is one of the most promising areas of this technology, scientists are still trying to grasp their astonishing complexities. Nanoscale analysis of Portland cement hydration products will allow more durable binders but the question related to when that will happen is not clear. The fact that nanoparticles are not cost-efficient prevents their commercial applications in a near future. Photocatalytic applications of nanomaterials are already a reality, still more research efforts are needed in order to find other semiconductors apart from TiO_2 and conductors that can be activated with visible light. Further research is also needed in the field of nanotoxicity, be there as it may, extreme caution must be used when using nanoparticles [15]. In another study on Beneficial role of nanosilica in cement based materials, demonstrated that Physical state and dispersion of nanosilica into the concrete is a major issue. Although various dispersing agents are in action, their feasibility in field is still questionable. A thorough study on dispersion mechanism is required and the optimum quantity of nanosilica for concrete or cement paste cannot be fixed with certain percentage. It all depends on the type of nanosilica (colloidal, dry powder, etc.) and the average particle size of nanosilica which can be expressed in terms of surface area to mass ratio. In this aspect a relationship should be established between optimum quantity and characteristics of nanosilica [16].

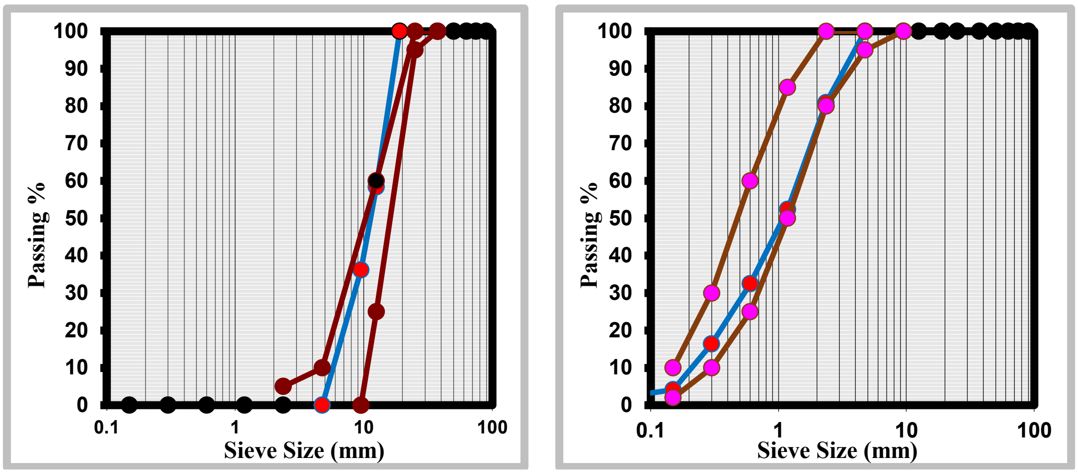
However, pozzolanic concrete has no proper formability, as compared to regular concrete. In addition, steel reinforcement bars have almost no influence on controlling and preventing the propagation of fine cracks within the concrete. This problem can be tackled by adding fibers to the concrete. This is performed to delay cracking and enhance toughness by transferring the stresses along the crack propagation direction to allow for much larger deformations under the maximum stress than non-fiber reinforced concretes. Thus, the present study adopted the friction-transfer test as a semi-destructive in-situ test [17] to examine the mechanical properties of polypropylene fiber-reinforced pozzolanic concretes. Then, the results were compared to those of the standard experimental tests. Next, using the friction-transfer test, the effects of polypropylene fibers on the shear bond strength between the repair mortar and steel substrate were evaluated. Previous studies demonstrated that the addition of fibers improved the behavior of the concrete under compressive stresses [18, 19], and positively influenced the stress-strain curve of the concrete [20]. Therefore in this article, this comparison was made and the relationships between the strength obtained from applying the 'friction transfer' test and the standard compressive, tensile, and flexural tests performed on the pozzolanic concrete containing glass and polypropylene fibers were presented. In addition, the effects of the fibers on the adhesion of the mortar and steel were evaluated using the friction-transfer test. Moreover, the 'friction transfer' test is also used for determining the strength of rocks [21] and bituminous pavements [22], and for measuring bond strength between the repaired layers and the concrete bed [23-26]. In reference [10], it is stated that there is a high correlation between the results of the 'friction transfer' test and the compressive strength of cubic concrete specimens.

To perform this study, 8 different mix designs with cubic compressive strengths ranging from 15 to 50 MPa were used. Then, glass and polypropylene fibers were separately added to each mix design at of cement. This study aims to present the calibration curves for the 'friction transfer' method using the experimental tests for determining the pozzolanic fiber concrete's strength and to investigate the effects of the type of the fiber on the results of the 'friction transfer' test. Moreover, the study investigates the stress distribution in the concrete specimens during the performance of the 'friction transfer' test. It should be noted that modeling and nonlinear analysis were performed using the finite element software, ABAQUS.

2- Experimental Works

2- 1- Materials

The specimens were made using gravel with a maximum size of 19 mm and sand with a maximum size of 4.75 mm, while grading was performed according to ASTM C136 Standard [27]. The amount of water absorption by gravel and sand, based on ASTM C128 [28] and ASTM C127 [29], was 2.6% and 3.2%, respectively. The gravel and sand densities at saturated surface dry conditions were 2330 and 2510 kg/m3, respectively. The grain size distribution curves for the gravel and the sand are depicted in Fig. 1.



a) Course aggregate

b) Fine Aggregate

Fig. 1. Aggregate grading diagram.

Table 1. Fibers Specifications.

Type of Fiber	Diameter (mm)	Length (mm)	Modulus of Elasticity (GPa)	Tensile Strength (MPa)	Special Weight (Kg/lit)
Glass	0.014	12	72	2600	2.7
Polypropylene	0.022	12	7	380	0.91

Table 2. Physical specifications of pozzolanic cement.

Cement type	Compressive strength (MPa)				Autoclave expansion (%)	Blain (cm^2/gr)	Initial setting (min)	Final setting (min)
	2 Days	3 Days	7 Days	28 Days				
Pozzolanic	12	17	26	50	0.08	3500	195	270

Table 3. Chemical specifications of pozzolanic cement (%).

Cement type	Fe_2O_3	SiO_2	Al_2O_3	CaO	Na_2O	K_2O	SO_3	MgO	LOI
Pozzolanic	4	27.25	4.67	56	0.58	0.45	2.2	2.87	1.98

The characteristics of glass and polypropylene fibers are given in Table 1. Also the characteristics of super-plasticizers used in making concrete are a type of polycarboxylate and a density of 1.11 Kg/Lit.

Tables 2 and 3 show the physical and chemical specifications of pozzolanic cement, respectively.

The presence of pozzolan in the concrete reduces the hydration heat in the concrete at its early age. This causes the 28-day compressive strength of the concretes made of type II cement to be greater than those made of pozzolanic cement. Another research studied the compressive strength of pozzolanic concrete and observed that the compressive strength of pozzolanic concrete was lower at an early age than that of regular concrete [30].

2- 2- Mix proportions

The mixing proportions of the concrete specimens using pozzolanic cement are presented in Table 4. The compressive strength is considered for 28 curing age. Moreover, the percentage of water absorption by the aggregates is calculated and added to the water used in the mix designs. In addition, the consistency and entrained air percentage of fresh

Table 4. Mix Design for Normal Concrete Samples (Fiber-free concrete).

Design Number	Compressive Strength (MPa)	Water ($\frac{Kg}{m^3}$)	Cement ($\frac{Kg}{m^3}$)	Water to Cement Ratio	Sand ($\frac{Kg}{m^3}$)	Gravel ($\frac{Kg}{m^3}$)	Superplasticizer ($\frac{Kg}{m^3}$)	Slump (mm)	Air Content (%)
1	15	221	328	0.67	901	716	0	4.7	**3/2**
2	20	215	356	0.6	888	707	0	4	**3/1**
3	25	211	381	0.55	879	699	0	3.1	**2.8**
4	30	206	416	0.49	864	687	0	2.5	**2.6**
5	35	198	440	0.45	862	686	1.17	6	**2.7**
6	40	195	476	0.41	851	677	1.61	5.7	**2.6**
7	45	191	516	0.37	838	667	2.12	5.5	**2.4**
8	50	187	534	0.35	835	664	2.61	5.3	**2.3**

Table 5. Super Plasticizer Specifications.

	CF**		SP* ($\frac{Kg}{m^3}$)
Design Number	Concrete+ polypropylene	Concrete+Glass	
1	0.93	0.92	0
2	0.92	0.92	1.62
3	0.92	0.9	2.05
4	0.91	0.88	2.43
5	0.89	0.88	2.97
6	0.90	0.89	3.41
7	0.88	0.87	4.02
8	0.88	0.86	4.45

*Super Plasticizer, **Compacting Factor

concretes are shown in this table as well. To make the fiber-containing concretes, the glass and polypropylene fibers were separately added to the admixture at 0.3 percent of concrete volume. To test the slump, a mold in the shape of a defective cone is used. The base diameter of this incomplete cone is 20 cm and its height is 30 cm. Fresh concrete is poured into the mold and then the mold is removed. The amount of fall and fall of concrete is measured and it is called the slump rate of concrete [31]. Standard ASTM C231 [32] has been used to determine the air content of freshly mixed concrete.

As adding fibers to the concrete reduces concrete workability, the workability of fiber-containing concretes is obtained using the compaction factor test, as shown in Table 5.

2- 3- Specimens make and experimental methods

To measure the rupture modulus of the concrete, a simple concrete prismatic beam with a size of $100\times100\times350$ mm without any reinforcement was tested using a loading point in the middle of the aperture according to the ASTM C293 Standard [33], as illustrated in Fig. 2. The loading mechanism included a loading block and two support blocks. A load as high as 3-6% of the estimated ultimate strength was applied to the specimen. Then, the specimen was monotonously loaded with no abrupt variations. The load increased at a constant stress rate of 0.86-1.21 MPa/min until the specimen ruptured. Then, the failed section of the specimen was measured three times (at the edges and the center), determining the mean width and mean depth of the specimen at the failure point.

Additionally, to determine the compressive strengths of the specimens by using the BS 1881-116:1983 Standard [34], a total of ninety-six 150-mm cubic concrete was fabricated. The internal surfaces of the molds were lubricated to prevent the adhesion of concrete and the mold before assembling the molds. The molds were to be filled in three layers. Each concrete layer was subjected to thirty-five impacts by a steel cubic bar with a size of 25 mm. The mold was filled to above

Fig. 2. The concrete rupture modulus test.

the edge. After compaction, the extra concrete content was removed using a metal ruler, and the upper surface of the specimen was flatted by a trowel. In the compressive test, the cubic specimens with perfectly flat sides (adjacent to the mold wall) were brought into contact with the test machine (i.e., a jackhammer concrete breaker). The loading direction of the cubic specimen during the test was perpendicular to its direction during concrete casting. Then, the loaded specimen was subjected to an enhancement rate of 0.15-0.35 MPa/s (i.e., 3375-7875 N/s).

To obtain the tensile strength according to the ASTM C496 Standard [35], a total of ninety-six cylindrical specimens with a diameter of 150 mm and a height of 300 mm were fabricated. The concrete cylinder was horizontally placed inside the jackhammer concrete breaker and was split into halves by applying a compressive load. This breakage arises from tensile stresses during the test and is a suitable method of determining tensile strength. The load should be applied monotonously with no abrupt variation at a rate of 689-1380 kPa/min until rupture occurs.

The specimens were cured within water for 28 days. Then, they were tested. To explore the effects of fibers on mortar-steel shear bond strength, mortar with a size of 150*150 mm and a thickness of 25 mm was applied onto a steel plate with a size of 200*200 mm. Then, a core with a diameter of 50 mm and a thickness of 25 mm was created by a core drill for different curing ages, as shown in Fig. 3a. Next, the system was subjected to the friction-transfer test, as illustrated in Fig. 3b.

In the “friction transfer” test, a partial core with a height of 25 mm height was first created in the concrete using a core drilling device, then the friction transfer device was fixed on the specimen, and a torsional moment was applied using a conventional torque meter until the partial core failed (Fig. 4). A total of sixty-four 150-mm cubic concrete specimens were fabricated for the friction-transfer test.

2- 4- Theory of the Friction Transfer Test

Since the concrete core in the friction transfer method is cylindrical with a circular cross-section, the shear stresses appear perpendicular to the radius of the circle produced by the torsional moment, as shown in Fig. 5a. In the elastic range, shear stresses are proportional to the distance from the center of the circle, and the majority of shear stresses occur on the circumference of the circle with the greatest distance from the center. In this case, the maximum amount of shear stress created by the torsional effect is (Eq. (1)):

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

Where r is the radius of the partial core and J is the polar

a) Core drilling

b) fixing the friction-transfer machine on the core

Fig. 3. Determining the shear bond strength between the fiber-reinforced mortar and steel

Fig. 4. Performing the "friction transfer" test.

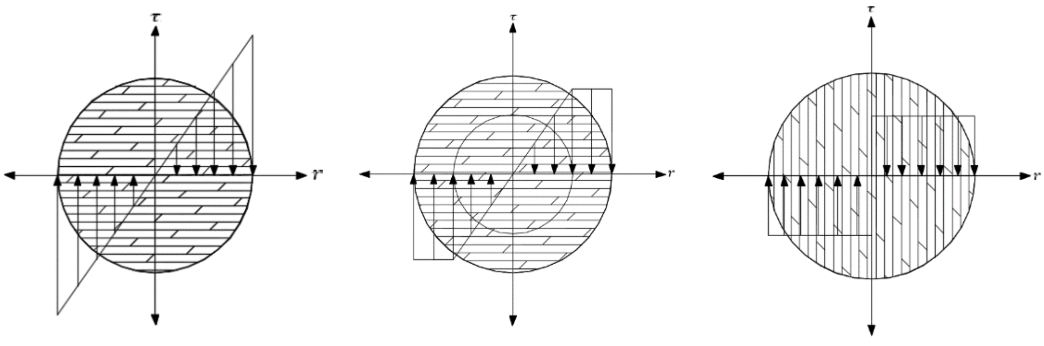


Fig. 5. Shear stress on the core.

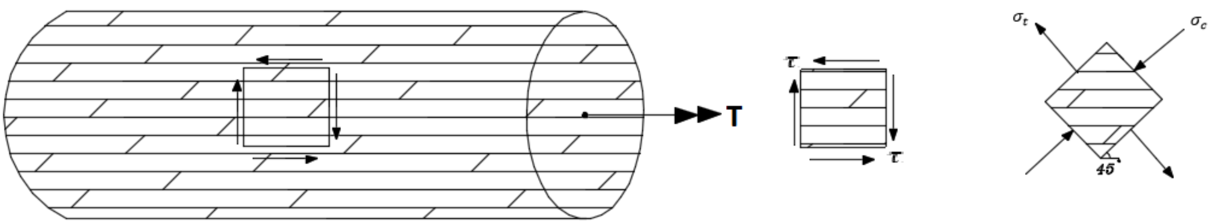


Fig. 6. Pure Shear on the core.

moment of inertia.

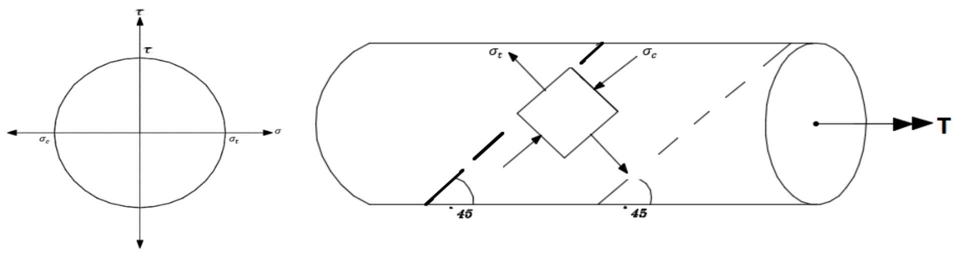
Then the yield onset begins at the surface of the object and proceeds within the bulk according to Fig. 5b until complete yield occurs and the material fails as in Fig. 5c. The maximum shear stress in the plastic state according to Eq. (2) is as follows:

$$\tau_{P-\max} = \int_0^r \tau_{\max} r 2\pi r dr = 2\tau_{\max}\frac{\pi r^3}{3} \rightarrow \tau_{P-\max} = \frac{3}{2}\frac{T}{\pi r^3} \quad (2)$$

According to Eqs. (1) and (2), it can be seen that the maximum shear stress in the plastic state is 0.75 times the elastic state. Concrete can also be considered a brittle matter.

2- 5- Core failure in "friction transfer" test:

In Fig. 6, a circular cross-section cylinder (such as a core in the "friction transfer" test) is shown under torsion. When only the torsional moment is applied in this section, the section elements are dominated by pure shear. Concerning the Mohr's circle on the rod surface, the maximum tensile stress and the maximum compressive stress in the cylinder under torsion are shown for the cylinder surface element in Fig. 6 .Considering the shape of Mohr's stress circle (Fig.



a) Mohr's circle **b) Fracture planes**

Fig. 7. Failure on the core.

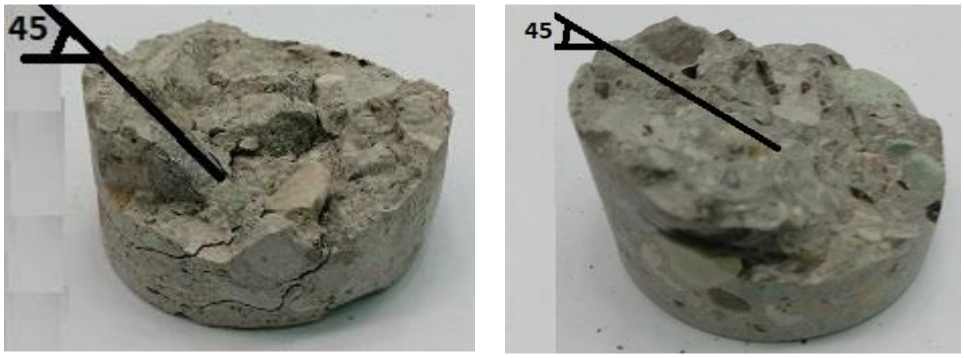


Fig. 8. The angle of failure on the core.

7a), it can be seen that the maximum shear, tensile and compressive stresses are all equal to the radius of Mohr's circle. In addition, the main tensile and compressive stresses make a 45-degree angle. Brittle materials such as concrete have tensile failure. As in Fig. 7b, fracture planes appear perpendicular to the tensile direction.

Fig. 8 shows examples of core fractures in the "friction transfer" test. It is observed that the failure of the cylindrical core in the "friction transfer" test builds a 45-degree angle to the horizon as explained above.

A scanning electron microscope (SEM) can shoot at different magnifications. This device is used to test and analyze the morphology of nanostructures. Image formation is performed using electrons reflected from the sample surface. In principle, this device is one of the methods of image production by scanning an electron beam on the surface of the sample. The wavelength of electrons is shorter than that of light photons, and shorter wavelengths provide sharpness, better information, and resolution. In the X-ray diffraction (XRD) test or material analysis test, it provides a graph of the intensity of X-rays scattered from the sample at different angles. In this device, it rotates in a circle around the sample. The position of the detector is recorded based on angle 2θ. At each stage, the detector detects scattered X-rays. Each phase creates its diffraction pattern, which is a specific atomic and chemical arrangement. In the XRD test, laboratory environmental conditions are temperature 20 ° C, humidity 37%, current 30 mA, counting time 0.5 seconds, and Cu anode. The SEM and XRD tests are considered for 28 curing age.

3- Results and Analysis

Regression analysis, which is used to predict the variations of a variable based on another one, was utilized in the current study. The present study fabricated standard experimental specimens to calculate the compressive strength, tensile strength, and flexural strength of fiber-reinforced pozzolanic concretes. Then, the friction-transfer test results were related to the aforementioned experimental results by using calibration curves in which the compressive, tensile, and flexural strengths of the concrete were treated as the dependent parameters (Y), while the corresponding friction-transfer results were employed as the independent parameter (X). In other words, the compressive, tensile, and flexural strengths of the concrete can be obtained by substituting the friction-transfer test results into the obtained equations. Regression analysis was used to investigate the relationship between the results of compressive and tensile strength and the rupture modulus of the concrete using the friction transfer test. Initially, correlation and determination coefficients were obtained using linear regression. Then, based on the hypothesis of the study positing that the regression line crosses the coordinate axis, and while setting the calibration equation $y = ax$, the regression analysis was performed to obtain the coefficient of determination. Finally, if there is a difference between the coefficients of determination obtained in the two abovementioned cases, power regression analysis can be used. In addition, the relation between compressive strength, the rupture modulus, and the tensile strength of the concrete is usually expressed as power regression [36], to obtain the correlation and determination coefficients between the friction transfer test and the tensile strength and concrete rupture modulus, statistical power regression analysis was utilized.

Overall, to measure compressive strength, a total of ninety-six 150-mm cubic specimens were fabricated. Furthermore, ninety-six prismatic specimens with a size of 100*100*350 mm were fabricated to obtain tensile strength. To measure the rupture modulus of concrete, a total of ninety-six cylindrical concrete specimens with a diameter of 150 mm and a height of 300 mm was built. For the friction-transfer test, sixty-four 150-mm cubic specimens were utilized. The specimens were unmolded and cured for 28 days in the water. Then, they were tested at the age of 28 days.

3- 1- Fiberless Pozzolanic concrete

Fig. 9 shows the results of the "friction transfer" test with compressive strength, tensile strength, and rupture modulus of concrete samples made with Pozzolanic cement.

It can be seen from Fig. 9a that there is a linear correlation with the intensity of 0.96 and the coefficient of determination of 0.94 between the compressive strength and the corresponding results of the friction transfer test. However, according to the research hypothesis positing that the regression line crosses the origin of the coordinates, the coefficient of determination was reduced to 0.89. Moreover, according to the 5% difference due to the elimination of the constant value from the linear regression equation, the power curve is used to a higher extent compared to the simple linear curve. The results showed that the correlation between the compressive strength and the corresponding results of the friction transfer test in a power model with the equation of $y = 5.86x^{1.33}$ was equal to 0.96, where y is the compressive strength of the pozzolanic concrete and x is the result of the friction transfer test. It can also be observed from Fig. 9b that there is a power correlation with an intensity of 0.96 and the coefficient of determination of 0.93 between the rupture modulus and the corresponding results of the friction transfer test. Therefore, to convert to the failure modulus of the pozzolanic concrete beams, the strength resulting from the friction transfer test can be substituted into the calibration curve equation, $y = 1.798x^{.79}$, to obtain the desired value in MPa with high confidence. It can be seen from Fig. 9c that there is a power correlation of 0.95 and a coefficient of determination of 0.91 with the equation $y = 1.298x^{0.66}$ between the tensile strength of the pozzolanic concrete and the corresponding friction transfer test results.

3- 2- Pozzolanic concrete containing polypropylene fibers

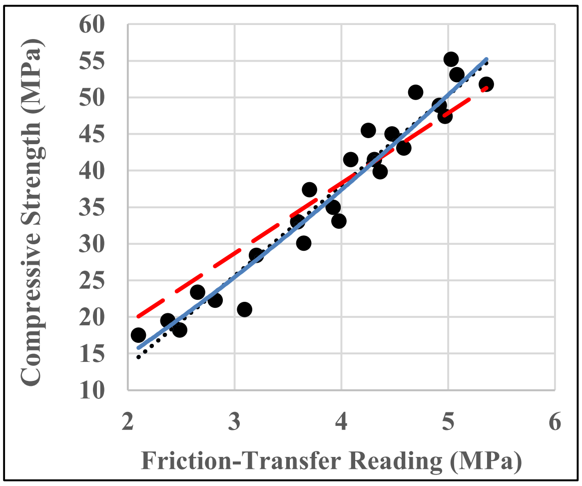
Fig. 10 shows the results of the "friction transfer" test with compressive, tensile strength, and rupture modulus of concrete specimens made of Pozzolanic cement containing polypropylene fibers.

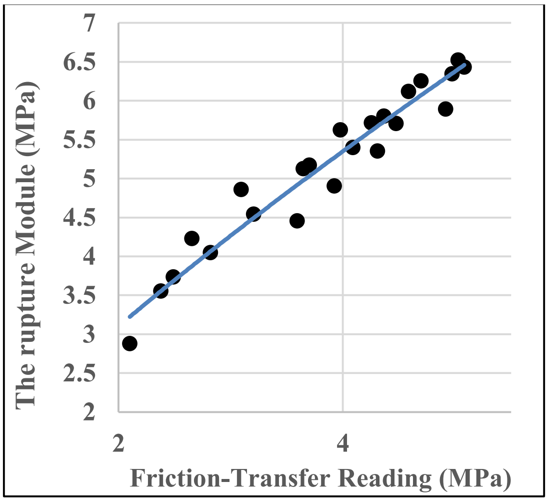
It is seen from Fig. 10a that there is a linear correlation between the compressive strength and the corresponding results of the "friction transfer" test for pozzolanic concrete containing polypropylene fibers with an intensity of 0.95 and the coefficient of determination of 0.92. But according to the research hypothesis that the regression line crosses the origin, the coefficient of determination was reduced to 0.86 and concerning the 6% difference due to the elimination of the constant value from the linear regression equation, one uses the power curve corresponding to the simple linear curve to a great extent. The results showed that the correlation between the compressive strength and the corresponding results of the "friction transfer" test for pozzolanic concrete containing polypropylene fibers was equal to 0.96 in a power model, $y = 5.66x^{1.36}$. It can also be seen from Fig. 10b that there is a power correlation with the intensity of 0.96 and the coefficient of determination of 0.93 between the rupture modulus and the corresponding results of the "friction transfer" test. Therefore, to convert to the failure modulus of the Pozzolini concrete beams, the strength resulting from the "friction transfer" test can be input to the calibration curve equation, $y = 1.299x^{1.016}$ and obtain the desired value in MPa with high confidence. It can be seen from Fig. 10c that there is a power correlation of 0.95 and a coefficient of determination of 0.92 with the equation $y = 1.18x^{0.76}$ between the tensile strength of pozzolanic concrete containing polypropylene fibers and the corresponding "friction transfer" test results.

3- 3- Pozzolani concrete containing glass fibers

Fig. 11 shows the results of the "friction transfer" test with compressive, tensile strength, and rupture modulus of concrete specimens made of Pozzolanic cement containing glass fibers.

It is seen from Fig. 11a that there is a linear correlation between the compressive strength and the corresponding results of the "friction transfer" test for pozzolanic concrete containing glass fibers with the intensity of 0.95 and the coefficient of determination of 0.91. But according to the research hypothesis that the regression line crosses the origin, the coefficient of determination was reduced to 0.88 and concerning the 3% difference due to the elimination of the constant value from the linear regression equation, one uses the power curve corresponding to the simple linear curve to a great extent. The results showed that the correlation between the compressive strength and the corresponding results of the "friction transfer" test for pozzolanic concrete containing glass fibers was equal to 0.95 in a power model, $y = 6.62x^{1.24}$. It can also be seen from Fig. 11b that there is a power correlation with the intensity of 0.96 and the coefficient of determination of 0.93 between the rupture modulus and the corresponding results of the "friction transfer" test. Therefore, to convert to the failure modulus of the Pozzolini concrete beams, the strength resulting from the "friction transfer" test can be input to the calibration curve equation, $y = 1.77x^{0.80}$ and obtain the desired value in MPa





$y = 12.327x - 11.352, R^2 = 0.941$ Linear … …

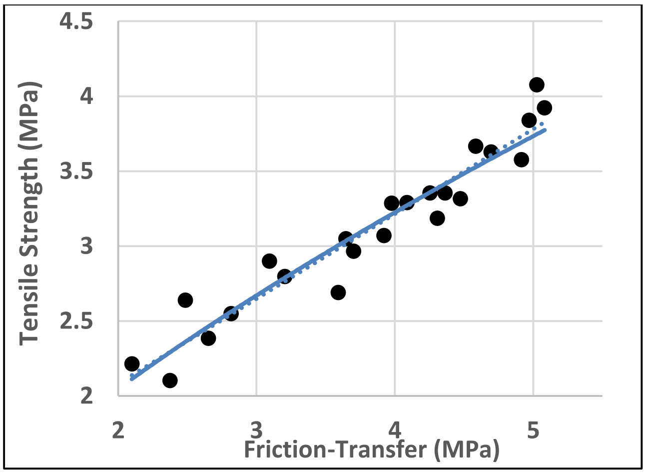
$y = 9.5743x, R^2 = 0.892$ Set Intercept - - - - - -

$y = 5.8589x^{1.333}, R^2 = 0.946$

a) Compressive Strength vs. "Friction-Transfer"

$y = 1.7986x^{0.786}, R^2 = 0.937$ **Power**

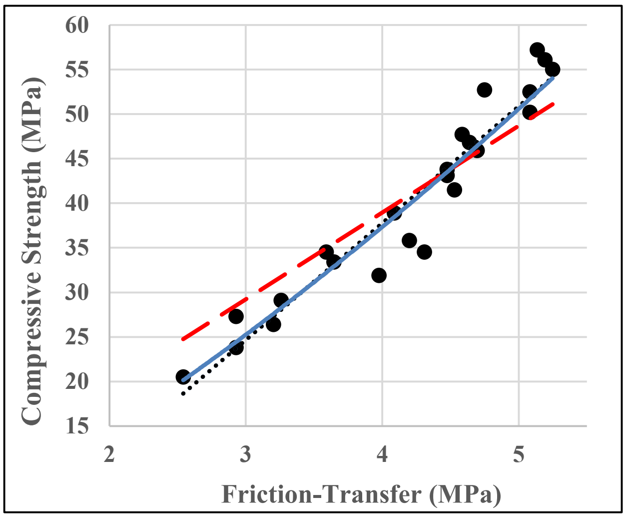
b) The Rupture Modulus vs. "Friction-Transfer"



$y = 1.2985x^{0.656}, R^2 = 0.914$ Power

c) Tensile Strength vs. "Friction-Transfer"

Fig. 9. Relationship between "friction transfer" test results with fiberless pozzolanic concrete strength.

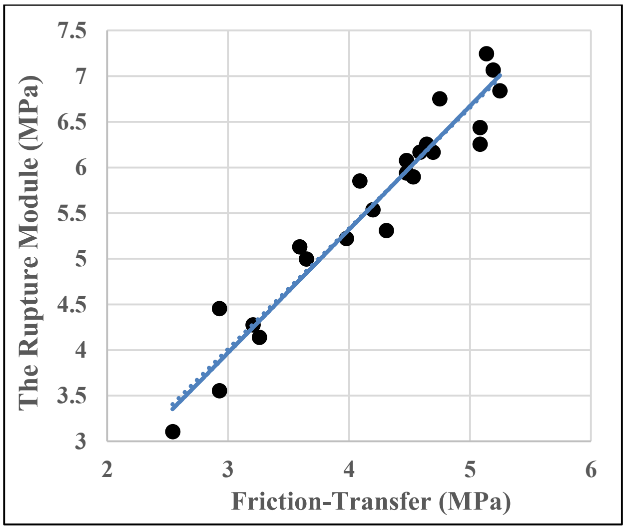


$y = 13.11x - 14.69, R^2 = 0.923$ Linear … …

$y = 9.7361x, R^2 = 0.86$ Set Intercept - - - -

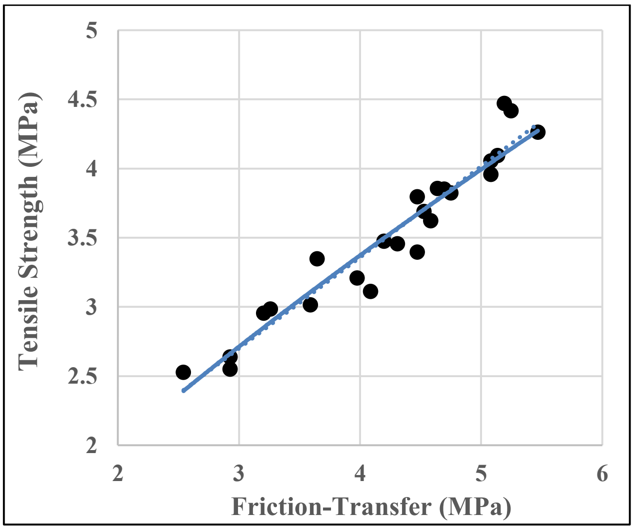
$y = 5.663x^{1.3606}, R^2 = 0.936$ Power

a) Compressive Strength vs. "Friction-Transfer"



$y = 1.2998x^{1.0163}, R^2 = 0.932$ **Power**

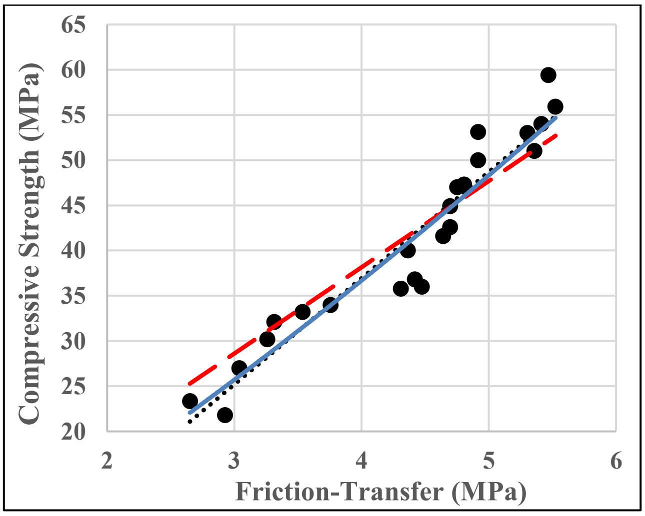
b) The Rupture Modulus vs. "Friction-Transfer"



$y = 1.1809x^{0.767}, R^2 = 0.929$ Power

c) Tensile Strength vs. "Friction-Transfer"

Fig. 10. Relationship between "friction transfer" test results with pozzolanic concrete strength containing polypropylene fibers.

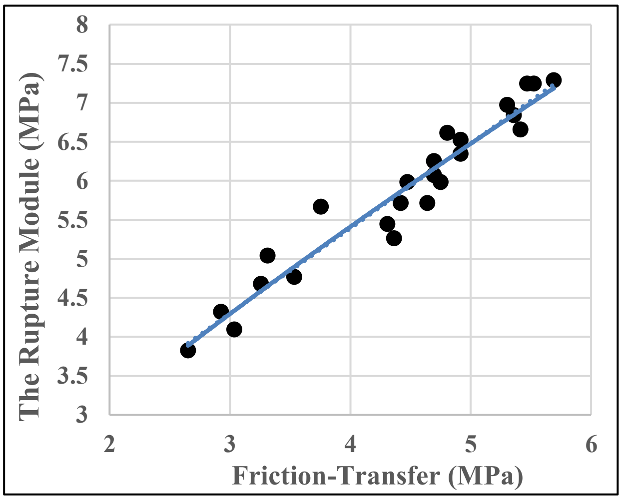


$y = 11.748x - 10.046, R^2 = 0.918$ Linear…

$y = 9.5354x, R^2 = 0.884$ Set Intercept - - - -

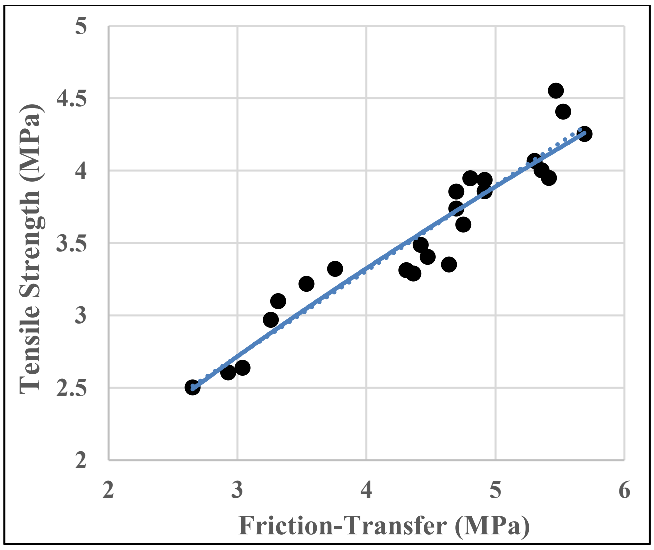
$y = 6.6195x^{1.2353}, R^2 = 0.926$ **Power**

a) Compressive Strength vs. "Friction-Transfer"



$y = 1.7736x^{0.8047}, R^2 = 0.937$ **Power**

b) The Rupture Modulus vs. "Friction-Transfer"



$y = 1.2562x^{0.7023}, R^2 = 0.915$ **Power**

c) Tensile Strength vs. "Friction-Transfer"

Fig. 11. Relationship between "friction transfer" test results with pozzolanic concrete strength containing glass fibers.

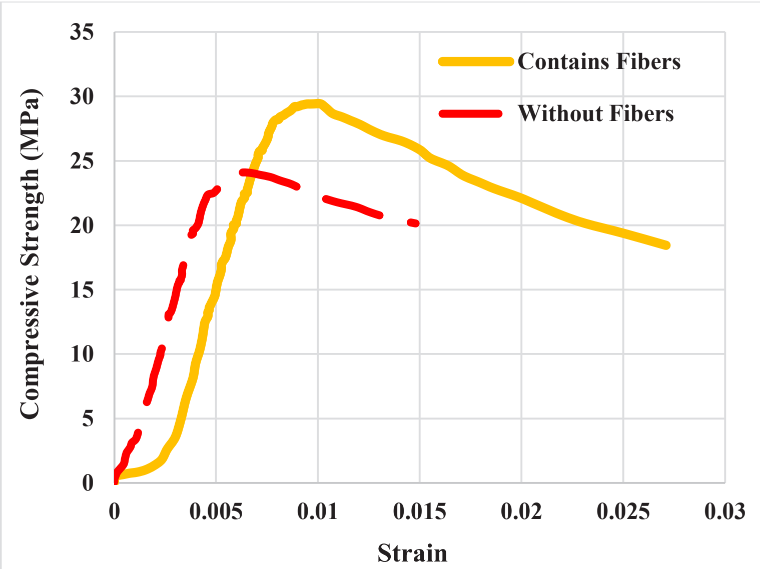


Fig. 12. Comparison between the behavior of concrete in two states of fiber-containing and fiberless specimens.

with high confidence. It can be seen from Fig. 11c that there is a power correlation of 0.95 and a coefficient of determination of 0.91 with the equation $y = 1.26x^{0.70}$ between the tensile strength of pozzolanic concrete containing glass fibers and the corresponding "friction transfer" test results.

In general, Figs. 9 to 11 indicate that there is a high correlation between the readings of the "friction transfer" test and the strengths obtained from standard laboratory tests on pozzolanic concrete with and without fibers, which as a result, the "friction transfer" test can be used as an in situ and reliable method for estimating the strength of pozzolanic concrete with and without fibers. In other research, evaluated the friction-transfer test and found a correlation coefficient of above 90% between the friction-transfer test results and the compressive strengths of cubic concrete specimens [17].

3- 4- Effects of the Fibers on the Results

The reason behind adding fibers to the concrete is to delay the cracking and increase toughness through the transfer of stresses along the width of the crack propagation path. In this way, there is a possibility of very large deformations under the peak stresses compared to concrete without fibers. Fig. 12 presents the behaviors of two concrete specimens, i.e., one containing fibers and one without fibers. According to Fig. 12, we see an increase in the toughness under pressure in the fiber-containing specimen. The fiber-free specimen failed at 24.1 MPa of stress, while the fiber-containing specimen was able to bear stress equal to 29.4 MPa. Failure of the fiber-containing specimen occurred at the strain rate of 0.0101, while in the fiber-free specimen, failure occurred at the strain rate of 0.006, indicating a decrease of about 40%.

Previous studies demonstrated that the addition of fibers improved concrete behavior under compressive stresses [18, 19] and positively influence the stress-strain curve of concrete [20].

Table 6 represents the compressive strengths, tensile strengths, and rupture moduli of the standard experimental specimens.

The results showed that the impact of the glass fibers on the compressive strength of the specimens was slightly greater than that of the polypropylene fibers. On average, the glass and polypropylene fibers increased the compressive strength of the cubic specimens by 13.1 and 9.7%, respectively, while they increased the rupture modulus of the concrete beams by 15.9 and 7.8%, respectively. Increasing the deformation corresponding to the ultimate flexural strength of the plain concrete will result in an abrupt failure. On the other hand, the fiber-containing concrete would sustain loads even at deformations much greater than those corresponding to the failure in the plain concrete. Therefore, fiber-containing concrete would not experience failure after the initiation of the first crack. Also adding fibers to the concrete increases the strength obtained from the 'friction transfer' test. The impact of fibers on the concrete specimens with lower strength is greater than on those with higher strength. In specimens with lower strength, adding the glass and polypropylene fibers has improved the results obtained from the 'friction transfer' test by 20 and 17%, respectively, whereas in specimens with higher strength the improvement was 7 and 4%, respectively. The use of polypropylene fibers makes the concrete uniform and has a positive effect on the tensile and compressive strength of concrete [37].

Table 6. Mechanical properties of pozzolanic concrete (MPa).

Design number	Pozzolanic concrete			Pozzolanic concrete + polypropylene			Pozzolanic concrete + glass		
	Compressive strength	Tensile strength	Flexural strength	Compressive strength	Tensile strength	Flexural strength	Compressive strength	Tensile strength	Flexural strength
1	18.4	2.19	3.3	22.3	2.57	3.36	23.1	2.58	4.08
2	22.2	2.52	4	27.6	2.98	4.29	30.1	3.12	4.83
3	30.5	2.79	4.62	33.2	3.24	5.14	34.3	3.28	5.47
4	35.2	3.03	5.13	36.4	3.43	5.54	37.3	3.41	5.79
5	41.5	3.27	5.43	42.8	3.72	5.98	43	3.74	6.19
6	44	3.32	5.72	46.8	3.83	6.17	48.1	3.92	6.4
7	49.3	3.62	6.15	51.8	4.03	6.48	52.7	4	6.92
8	53	3.95	6.38	56.1	4.38	7.05	56.2	4.4	7.17

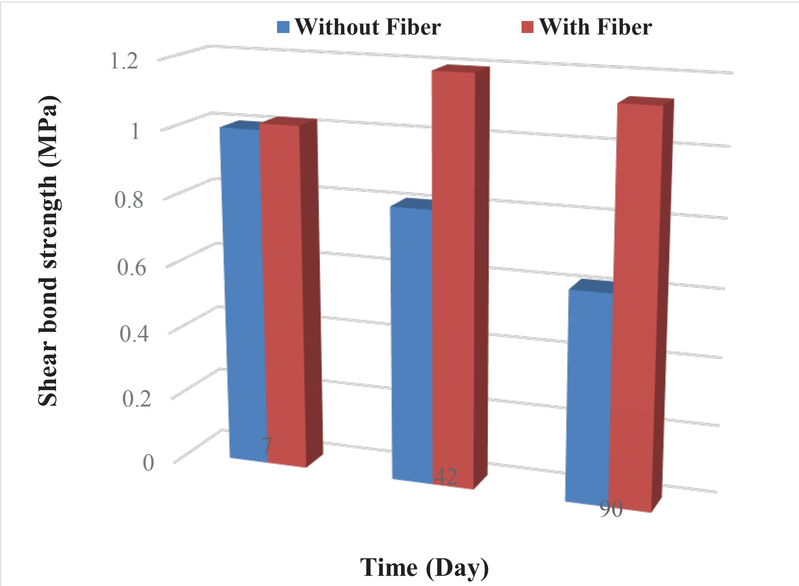


Fig. 13. The shear bond strength of the reinforced/non-reinforced mortar and the steel substrate in the friction-transfer test.

3- 5- Effect of the cement type on the results of the 'friction transfer' test

Similar to the pozzolanic concrete, 8 different mix designs with type II cement were prepared, and they were subjected to friction transfer and compressive strength tests. Afterward, the results of these tests were compared to those conducted on the pozzolanic concrete. The results showed an increased compressive strength of the specimens made of type II cement compared to the pozzolanic concretes, which was improved by 6.2% on average. The reason for this result can be attributed to the presence of pozzolan in the concrete which reduces the hydration heat in the concrete at its early age. This causes the 28-day compressive strength of the concretes made of type II cement to be greater than those made of pozzolanic cement. Performing the friction transfer test also yielded similar results. The results of the friction transfer test performed on the concrete made of type II cement were on average about 10% higher than the results obtained for the pozzolanic concrete. In other research, studied the compressive strength of pozzolanic concrete and observed that the compressive strength of pozzolanic concrete was lower at an early age than that of regular concrete [30].

3- 6- Shear bond strength of the friction-transfer test

This section investigates the shear bond strength between the polypropylene fiber-reinforced mortar and steel substrate by using the friction-transfer test. The water/cement ratio was 0.5, while the sand/cement ratio was 3. Fig. 13 demonstrates the shear bond strength between the reinforced/non-reinforced repair mortar and the steel substrate obtained from

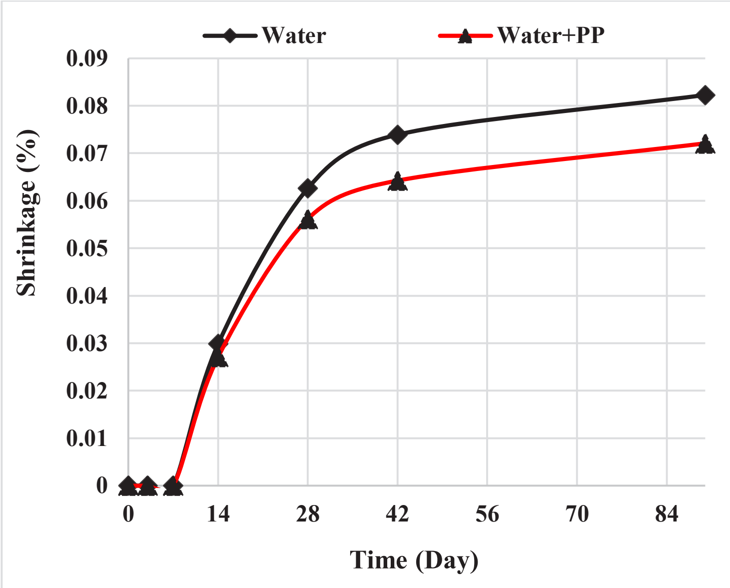


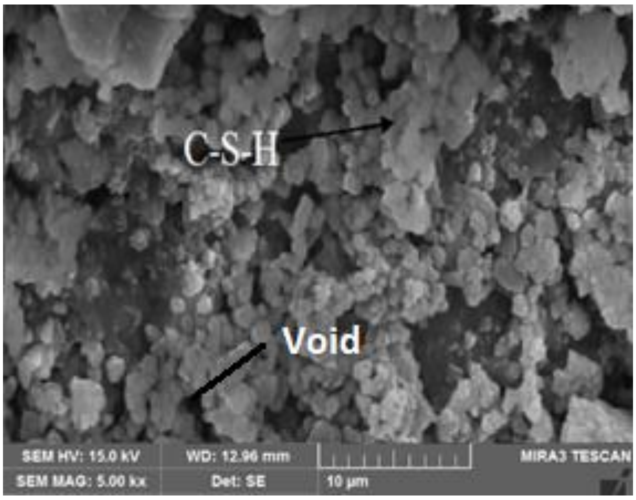
Fig. 14. The shrinkage of non-reinforced mortar versus polypropylene-reinforced mortar.

the friction-transfer test.

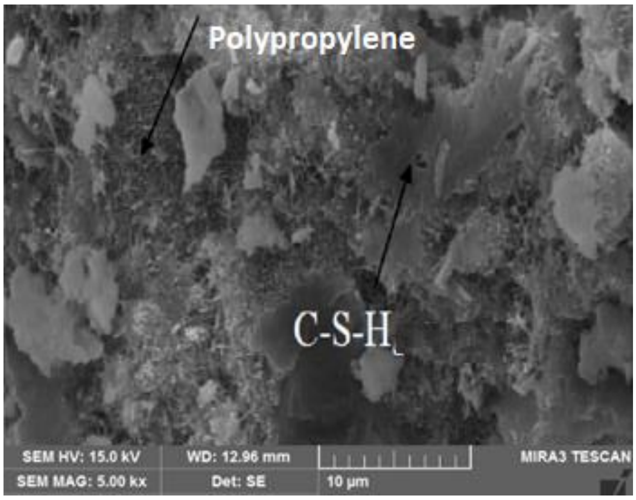
As can be seen in Fig. 13, the addition of fibers to the repair mortar significantly affected the shear bond strength enhancement of the repair mortar and steel substrate in the friction-transfer test. However, a small change in the 7-day shear bond strength is observed since mortars were cured for up to seven days within the water. The shear bond strength between the conventional repair mortar and the concrete substrate was obtained to be 1.001, 0.809, and 0.617 MPa at the ages of 7, 42, and 9 days, respectively, in the friction-transfer test. However, the shear bond strength was found to be 1.02, 1.196, and 1.137 MPa for the fiber-reinforced mortar at the ages of 7, 42, and 90 days, respectively. The addition of polypropylene fibers to the repair mortar enhanced the shear bond strength by 48% and 84.3% at the ages of 42 and 90 days, respectively, in the friction-transfer test. An explanation for the larger shear bond strength of the reinforced mortar than that of the non-reinforced mortar in the friction-transfer test was the reduced shrinkage of the fiber-reinforced mortar as it decreased the cracks, preventing the decline of shear bond strength between the mortar and steel. Fig. 14 depicts the shrinkage results of the repair mortars. The mortars were cured for a week. Then, their shrinkage was calculated at different ages. The shrinkage of the non-reinforced mortar at the age of 90 days was observed to be 0.0720%. In other words, the addition of fibers to the mortar decreased the shrinkage by 11.1% on average at the age of 90 days, which directly affected mortar-steel adhesion. In a similar work, [38] suggested that a large portion of drying-induced shrinkage occurred at an age of up to 42 days, and shrinkage substantially decreased above the age of 90 days.

Fig. 15a illustrates the SEM image of the non-reinforced concrete. As can be seen, C-S-H gel formed due to the hydration of C_3C and C_2S. However, some voids are observed within the concrete, which can substantially contribute to the strength reduction of concrete.

According to Fig. 15b, the SEM images suggest that the addition of polypropylene fibers to concrete led to the better hydration of cement, the formation of C-S-H gel in the vicinity of polypropylene fibers, and a more uniform concrete composition. In other words, the addition of polypropylene fibers improved concrete bonding. Moreover, the fibers functioned as a bridge between the cracks and prevented the width enhancement of the cracks. In other words, the fibers not only reduced the number of cracks but also stitched the cracks. To obtain a better insight into the phases and crystallographic structure of the particles within the concrete before and after the addition of polypropylene fibers, the XRD test was carried out on the specimens. Fig. 16 demonstrates the XRD results. As can be seen, the addition of fibers decreased the $Ca(OH)_2$ peak indicated by a black arrow. In fact, C-S-H gel increased as $Ca(OH)_2$ was consumed. The transformation of the $Ca(OH)_2$ content within the concrete structure into C-S-H can affect the ultimate properties of concrete, enhancing the strength of concrete.



a) non-reinforced concrete



b) fiber-reinforced concrete

Fig. 15. The SEM image.

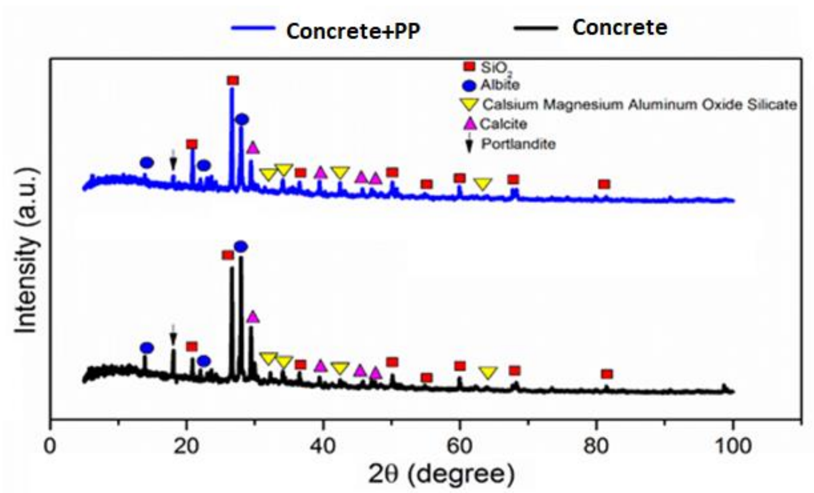
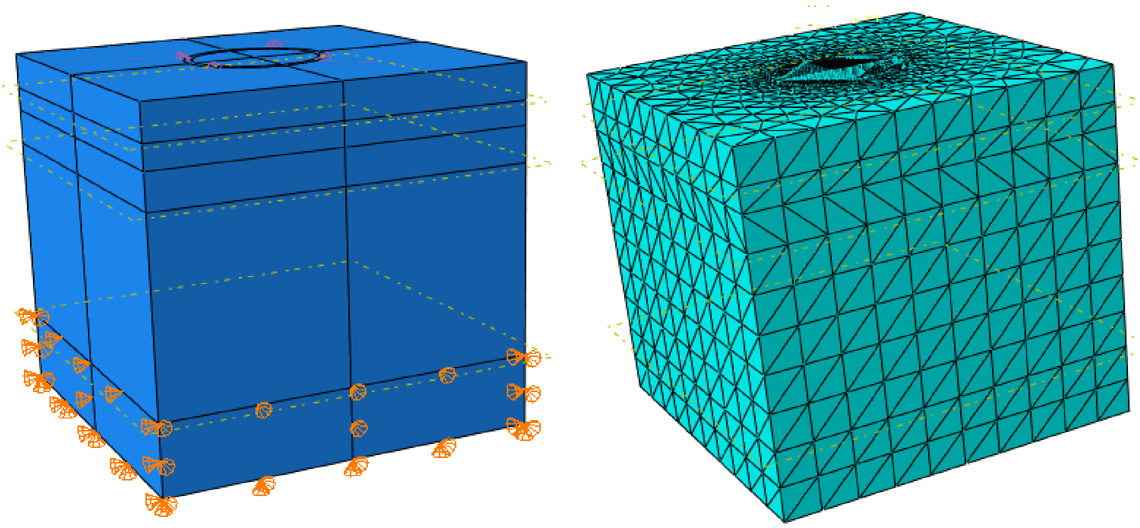


Fig. 16. The XRD pattern.

3- 7- Modeling the 'friction transfer' test using the finite element software ABAQUS

Determining the nonlinear behavior of the concrete is the most important stage in the numerical modeling of reinforced concrete structures. In the finite element software Abaqus, the nonlinear behavior of brittle materials can be defined by three approaches, i.e., the smeared cracking model, the brittle cracking model, and the concrete damaged plasticity model. Each model has several advantages which can be used based on the conditions. The concrete damage plasticity model is the only one that can be incorporated in both static and dynamic analyses. In this model, it is assumed that tensile cracking and compressive crushing are the two main aspects of the failure mechanism in concrete. Due to the lack of a failure criterion in the concrete damage plasticity model, it is not possible to remove elements during the analysis or crack formation; however, the model can predict the location and the direction of the formation of cracks. To introduce the materials, the stress-strain curve, and other necessary values, the 'module properties' section and the 'create material' command were utilized. The other stages, including the meshing, were performed using the commands available in the software application. To define the supports in the friction transfer test, similar to the one performed in the laboratory, the concrete specimens were kept in a steel frame with a height of . Therefore, the supports were also defined in the



a) boundary conditions **b) meshing of the specimens**

Fig. 17. Definition of boundary conditions and Meshing of the specimens in the 'friction transfer' test.

modeling according to Fig. 17a.

One of the main points in the meshing of the specimens is convergence. The obtained results in the finite element method problems are highly dependent on the size of meshes. Reducing the size of elements helps with convergence to a single response. Due to the dependence of responses to the size of meshes, therefore in portions of the model where there is a need for precise stress, strain, etc. values the convergence of meshing should be checked. But in areas that are far from the stress concentration points the meshing size could be taken larger. In the 'friction transfer' test, the meshing of the cubic concrete mold is a combination of C3D8R and C3D4 elements. The meshing of the main portion of the model which is under tension or compression is done using the eight-node brick element with reduced integration, C3D8R. The size of elements in this modeling has been taken equal to 1mm which after convergence was selected between 0.5, 1, and 2 mm. Also, the edges are meshed by continuous four-node tetragonal elements and a minimum size of 1mm at the location of their connection to the main elements. The maximum size of elements was taken at 15 mm at the edges (Fig. 17b).

For modeling purposes, use was made of two experimental specimens; with and without fibers. The specimen which lacked fibers had a compressive strength of 24.1 MPa and the other which contained polypropylene fibers had a compressive strength of 29.4 MPa, also their behavior is according to what is shown in Fig. 12. the results of the 'friction transfer' test for the specimen lacking fibers was equal to 76 N.m and for the specimen containing fibers is equal to 89 N.m. In modeling the 'friction transfer' test the torque was applied in the form of rotational motion around the core axis concerning the core perimeter using the coupling constraint.

According to Fig. 18, in the modeled specimens, the ultimate torque which causes rupture of the concrete core in the fiberless pozzolanic concrete was 71 N.m. Whereas in the case of fiber-containing specimens this value increased to 92 N.m. It is observed that the results of the finite element analysis have high compatibility with the experimental ones.

Also, the fiber-containing pozzolanic concrete concerning the fiberless concrete had more flexibility and the maximum strain rate at the critical load which was 0.0073 radians in the fiberless pozzolanic concrete reached 0.02 radians in the fiber-containing pozzolanic concrete. This clearly shows improvement in the concrete properties. Investigating the comparison diagram in the above figure it is observed that the fiberless pozzolanic concrete is more brittle and does not exhibit significant strain up to 63 N.m torque and failure occurs in this specimen abruptly. Whereas in the fiber-containing specimen the diagram is smoother with a lower slope and the addition of fibers causes toughness in the material. In the fiberless pozzolanic concrete, we observe two force peaks and the first peak occurs at 65 N.m torque. At this time maximum damages are seen at the edges which causes failure at the edges. But as the cracks have not reached each other within the specimen the model after a peak of force and reduction in the torque value again resumes its ascending trend.

According to Fig. 19, the first cracks initiated at the edges and corners of the fiberless pozzolanic concrete specimen at 7 N.m which were under maximum torque. Whereas the first cracks initiated at 13 N.m torque in the fiber-containing specimen. In the fiberless specimen, damages are gradually reached each other and cause cracks at the edges per 65 N.m

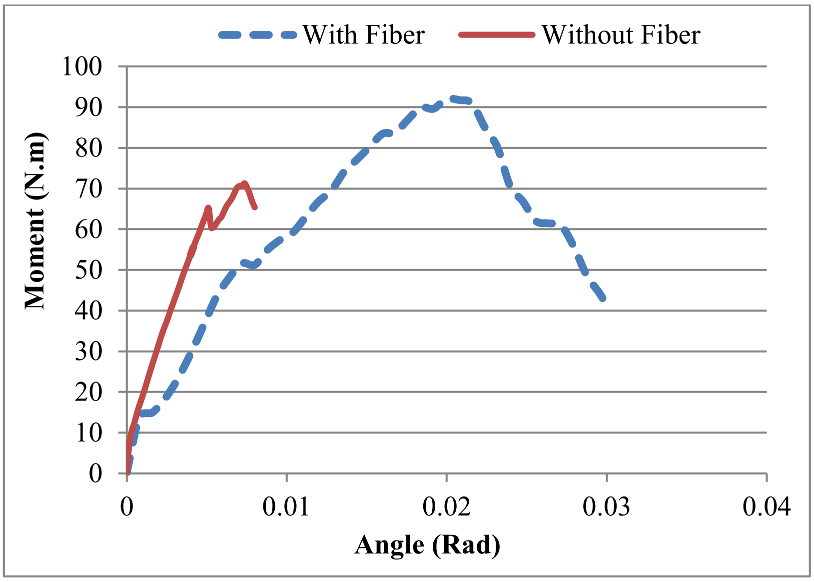
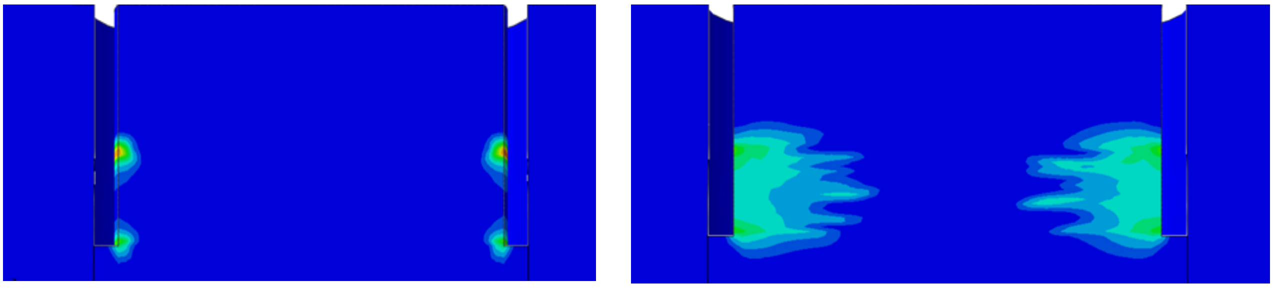


Fig. 18. Comparison between the results of fiber-containing pozzolanic concrete and fiberless pozzolanic concrete.



a) Without Fiber **b) with Fiber**

Fig. 19. Crack initiation in the cores.

torque. Then the torque is increased again and ultimately all the cracks reach each other at 71 N.m torque which results in overall damage to the specimen. After that and by a reduction in the strength of the specimen we experience reduced torque. In the fiber-containing specimen, damages occurred at the edges per 83 N.m torque. Then at 92 N.m torque, cracks reached each other in the middle of the specimen, and a rupture occurred.

In the fiberless pozzolanic concrete at the first peak point, the specimen is near without damage, from this moment on, damages occur at the edges of the specimen. The maximum induced stress reaches 11 MPa. Next, at the moment of applying the critical torque, stresses in the specimen reach the ultimate compressive stress of about 18 MPa. This value for the fiber-containing concrete is equal to 30 MPa. Also, this value for the fiberless concrete increased by a reduction in the cross-sectional area and reached up to about 22 MPa. The maximum stress in the fiber-containing model also reached up to 42 MPa (Fig. 20).

4- Conclusion

The present study evaluated the compressive strength, tensile strength, and flexural strength of fiber-reinforced pozzolanic concrete and obtained the shear bond strength between the fiber-reinforced concrete and steel by using the friction-transfer test. Furthermore, ABAQUS was employed to model the friction-transfer test and compare the results to experimental results. The findings can be summarized as:

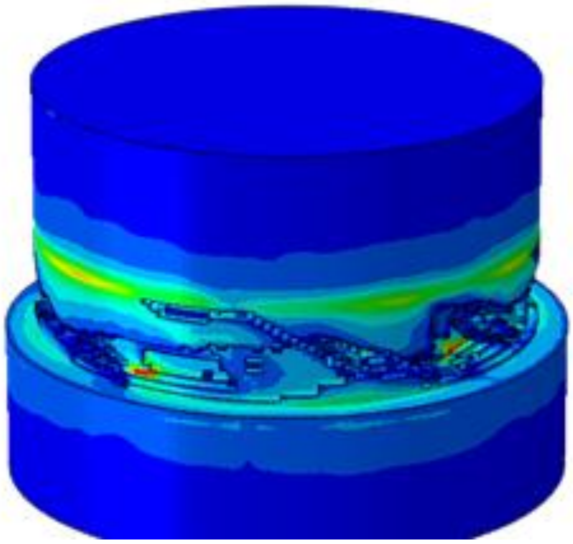


Fig. 20. Core Failure.

- The equations of $y = 5.86x^{1.33}$, $y = 1.29x^{0.65}$ and $y = 1.79x^{0.78}$ are proposed to translate the friction-transfer results for the compressive strength, tensile strength, and flexural strength of pozzolanic concrete, respectively.

- Since a large correlation coefficient was obtained, the friction-transfer test can be employed to evaluate the compressive strength, tensile strength, and flexural strength of glass/polypropylene fiber-reinforced pozzolanic concrete.

- The addition of fibers to pozzolanic concrete increased compressive strength and flexural strength by 9.7% and 8.7%, respectively.

- The results of 'friction transfer' and compressive strength tests in concretes made of cement type 2 are respectively 11% and 6.2% greater than the results of specimens made of pozzolanic cement.

- The difference between the experimental friction-transfer results and FEM findings was found to be smaller than 3.5%. This suggests the high accuracy of the friction-transfer test.

- The addition of polypropylene fibers to the mortar diminished the shrinkage by 11.1% at an age of 90 days.

- The addition of polypropylene fibers to the mortar increased the shear bond strength between the mortar and steel by 48% and 84.3% at the ages of 42 and 90 days in the friction transfer test, respectively.

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