NUMERICAL AND EXPERIMENTAL STUDY OF SEMI-DESTRUCTIVE TESTS TO EVALUATE THE COMPRESSIVE AND FLEXURAL STRENGTH OF POLYMER-MODIFIED MORTARS AND THEIR ADHESION TO THE CONCRETE SUBSTRATE

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In this paper, the flexural and compressive strength of polymer-modified mortars (PMM), using the "Twist-off" and "Pull-off" semi-destructive tests has been evaluated. The shear and tensile bond strengths between the PMM and the concrete substrate have also been investigated. The SBR Latex has been used in mortars with 10, 15, and 20% ratios of cementitious materials. The correlation between the results obtained from experimental tests and semi-destructive tests at different ages using linear and power regression analysis was determined, and the calibration curves were presented. Calibration curves can be used to convert the results of the "Twist-off" and "Pull-off" tests to the compressive and flexural strength of PMM. In the following, the effect of polymer content on shrinkage and bond strength of repair mortars with the concrete substrate was investigated. Furthermore, to investigate the obtained stress results during semi-destructive tests, the "Twist-off" and "Pull-off" tests were analyzed by utilizing the ABAQUS finite element analysis software. The results showed a high correlation between the mechanical properties of polymer-modified mortars and the resulted data of semi-destructive tests, and high compatibility with the numerical analysis was observed. Moreover, due to the high correlation between shear and tensile bond strength resulting from "Twist-off" and "Pull-off" tests, it is possible to use a simple and inexpensive "Twist-off" machine instead of using an expensive "Pull-off" machine

Keywords: *"Twist-off", "Pull-off", finite element method, polymer-modified mortar, strength*

1. Introduction

Nowadays, polymers are used as a modifier for improving some of the cement mortars properties. Frequent studies have been carried out to investigate the effect of the polymer on the cement mortars. In a study on the effect of SBR latex on the repair mortars with various SBR-to-cement ratios of 5, 10, 15, and 20%, it was included that adding the polymer decreases the mortar density, that the lowest density was observed in the ratio of 5% [1]. The use of SBR increases the porosity, and on the other hand, increasing the ratio of polymer-to-cement decreases the water permeability [2]. SBR increases the amount of air bubble inside the mortar that makes the holes and porosity, which leads to the compressive strength decrement of the mortar [3]. In general, the conducted studies show the negative effect of the SBR on the compressive strength of mortar but increases the flexural strength significantly [4,5]. Improving the adhesion between repair mortar and the concrete substrate is one of the important properties of SBR so that the mortar modified by SBR has greater adhesion compared to conventional mortar [6].

The tests performed on the polymer-modified mortars were carried out experimentally. Considering that the experimental tests show the properties of the mortars in the special conditions, and according to the factors such as neglecting to the curing method, the real condition of the structure, the humidity of the laboratory site, and the difference in the keeping temperature, the mortar cannot be the presenter for the mortar applied in the various parts of the intended structure. Measuring the mechanical properties of the cement in situ are categorized to three types of destructive, semi- destructive, and non-destructive. The “coring” [7] and “pull-out” [8] tests can be mentioned as the destructive tests, which have some disadvantages definitely due to the limited iteration capability and the damages applied to the element. Besides, several researches have shown that the compressive strength of the cores is less compared to the real compressive strength [9]. The non-destructive tests such as ultrasonic [10] and Schmidt Hammer [11] also evaluate the strength of the cement materials indirectly. The “Pull-off” [12], “Friction-Transfer” [13] and “Twist-off” [14] tests are some of the semi-destructive methods. Whereas the fracture occurs in the sample itself in the semi-destructive tests, the results of these tests have higher validity compared to the surface stiffness determination test or the tests, in which the material strength are determined indirectly.

In this study, the semi-destructive “Pull-off” and “Twist-off” tests were used to evaluate the in situ mechanical properties of the SBR polymer modified mortars and their adhesion on the concrete substrate. The previous studies were used the “Friction-Transfer” and “Twist-off” tests for evaluating the strength of concrete [15-18], rock [19], bituminous pavements [20], and the mortar

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adhesion to the concrete substrate [21-23]. The correlation of the results of the “Pull-off” and “Twist-off” tests and the compressive and flexural strength of the polymer-modified mortars was determined using the regression analysis and the calibration diagrams were drawn. For this purpose, the repair mortar was produced with various SBR latex–to-cement ratios (10, 15, and 20%) and was experimented in the ages of 3, 7, 28, 42 and 90 days. Besides, the effect of SBR polymer on the repair mortars shrinkage and their adhesion on the concrete substrate were investigated. Finally, the modeling and analysis of the “Pull-off” and “Twist-off” tests were carried out using the ABAQUS finite element software.

2. Experimental works

2.1. Materials

The consumed was Portland cement type 2 with a density of 3700 kg/m^3 The maximum granule size of gravel and sand was 19 and 4.75 mm, respectively. Their absorption rate, were obtained 2.6 and 3.2 %, respectively based on the ASTM C128 [24] and ASTM C127 [25] standards. The Sand and gravel were granulated based on the ASTM C136 standard [26]. The density of sand and gravel in the saturated surface dry condition were 2510 and 2330 kg/m^3. The two-part epoxy resin adhesive with the one by one combining volume was used.

2.2. The substrate concrete and the repair mortar

The mix design of the substrate concrete has been shown in Table 1. The 28-day compressive strength of the concrete substrate was 57 MPa. Due to instability of the aggregates humidity in the open space, sand and gravel were kept in the laboratory environment for 72 hours primarily then their water absorption was calculated to reach the saturated dry surface and was added to the mixt water. The repair mortar has the water-to-cement ratio of 0.5 and the sand-to-cement ratio of 2, and the SBR latex with the ratios of 10, 15 and 20% of the cement weight was added to the mortar.

2.3. Making the samples

To provide the concrete of the substrate, the cubic concrete samples with the dimensions of 150 mm were made and flooded in the water for 60 days, primarily. Afterward, they got out of the water. The concrete saw was used to make the surface smooth with appropriate strength and each sample was divided into three parts with a cross-section of 150*150 mm and a height of 50 mm. Along with applying the repair layers, the samples were made for determining the compressive and flexural strength and shrinkage of mortar and got out from the mold after 24 hours and flooded in the water. The mortars were placed into the water until the start of experiment time. To evaluate the compressive and flexural strength using “Pull-off” and “Twist-off” tests, they were tested after getting out from the water in the ages of 3, 7, 28, 42 and 90 days. To investigate the effect of SBR on the shrinkage and adhesion between mortar and the concrete substrate, all the samples were got out from the water after one week and were abandoned in the laboratory space, and then, were tested in the ages of 7, 42 and 90 days.

2.4. The experimental methods

The Twist-off test was applied to determine shear bond strength. In the twist-off test, the core drilling machine first created a partial core from the mortar surface to the substrate concrete, then the steel cylinder was bonded to the core surface using Epoxy resin-based adhesives, and a conventional Torsion Testing Machine inserted a twisting moment into the steel cylinder to separate the core from the concrete surface (Fig. 1a). Moreover, in order to evaluate the mortar compressive and flexural strength, 150 mm cubic samples were made and a steel cylinder adhered to the surface without core drilling; after which a twisting moment was inserted into the steel cylinder by using Torsion Testing Machine to separate crushed mortar and the cylinder from mortar surface (Fig 1b).

Fig. 1 - Performing "Twist-off" Test; a) The determination of shear bond strength, b) the evaluation of repair mortar compressive strength.

As can be seen in Fig. 2a, the partial core is a cylinder with a circular cross-section in this method. As evident in Fig. 2a, if the twisting moment is applied, maximum shear stresses will occur on the circumference of the circle that has

Table 1

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

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

the furthest distance from the center. The failure between common surfaces has different forms: failure occurs at the common boundary between the repair mortar and the concrete substrate (Fig. 2b), failure occurs within the mortar or substrate concrete, or failure is a combination of both forms (Fig. 2c). Given that maximum stress occurs at the farthest distance from the center if a composite failure occurs, Fig. 2c shows that failure did not occur at the center but at the farthest distance from the center.

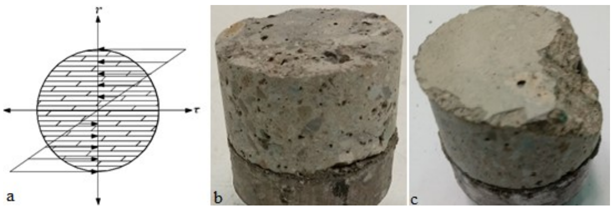


Fig. 2 - Creation of Stress and Failure in the "Twist-off" Method; a) Maximum shear stress, b) failure at common boundary, c) composite failure.

The maximum shear stress created by the twist-off method is calculated as (Eq. 1):

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

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

The “Pull-off” test, was also employed to measure the tensile bond stress and evaluation of in situ mechanical properties of mortars. To measuring the adhesion, a core was made in the surface of the repair mortar and it continues up to a height of 10 mm into the substrate surface. Afterward, the metal cylinder is attached to the core using epoxy resin adhesive, and the force is applied to it by the puller machine until the core was separated from the substrate surface. In addition, to evaluate the mechanical properties of the mortars coring, the metal cylinder is attached on the surface of the sample, and then by applying the tensile force, the mortar was fractured and separated from the cylinder. The ASTM C157 [27] and ASTM C490 [28] standards were used to determine the shrinkage of the mortars. According to the standard, at least three prismatic sample with the square cross-section of 25 mm dimensions and 285 mm height must be tested. Also, the ASTM C109 [29] and ASTM C190 [30] standards were used for evaluating the compressive and flexural strength of the mortars respectively. For measuring the compressive strength of the mortars, six 50 mm cubic samples must be made for each type of mortar and their mean value must be determined. Also for measuring the flexural strength, the average of three experiments with the dimensions of 40*40*160 mm must be studied.

3. Results and analysis

3.1. Assessment of compressive and flexural strength with semi-destructive tests

Through a regression analysis in the linear and exponential situation, the relation between compressive and flexural strength of polymer-modified mortars are presented utilizing semi-destructive tests of “Twist-off” and “pull-off” in this section. Firstly, the coefficient of determination was specified among the obtained perusals from the above-mentioned tests on the compressive strength of mortars by conducting linear regression analysis. In the following, the coefficient of determination has been calculated again regarding the “Research hypothesis” that expresses that “the regression should have passed through the coordinate system, its calibration equation should be chosen a y=ax, and then, the regression analysis could be performed”. In the end, the regression analysis can be used in exponential mode if there is any discrepancy between attained coefficients of determination from aforesaid analyses. Moreover, since the relation between flexural and compressive strength is usually in an exponential situation, hence, the regression in exponential mode is also utilized in this section for measuring the coefficient of determination between flexural strength and in-situ tests.

3.1.1. Obtained results from “Twist-off” test

The relation between the compressive and flexural strength of mortars and obtained results from the “Twist-off” test is illustrated in Fig. 3.

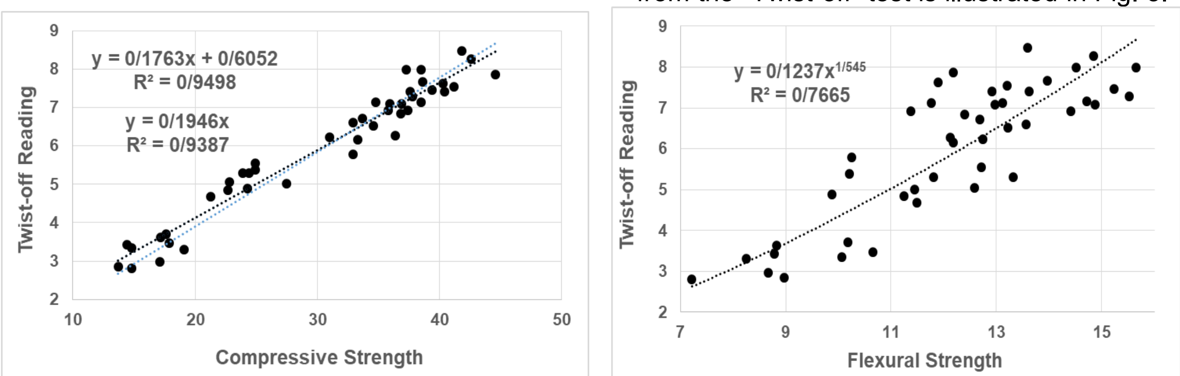
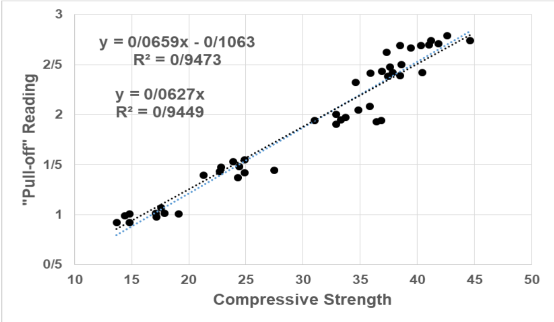


Fig. 3 - Correlation between compressive and flexural strength and results of “Twist-off” test (MPa); a) compressive strength - “Twist-off” test, b) flexural strength - “Twist-off” test.



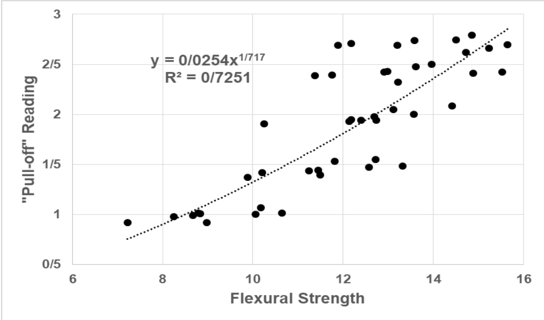


Fig. 4 - Correlation between compressive and flexural strength and results of "Pull-off" test (MPa); a) compressive strength - "Pull-off" test, b) flexural strength - "Pull-off" test.

According to Fig. 3a which is about the regression analysis between compressive strength and obtained results from the "twist-off" test, it is observed that the coefficient of determination is equal to 0.949 in linear mode. However, regarding the "research hypothesis", if the regression equation is chosen in a linear mode as y=ax and the regression analysis is performed again, then the coefficient of determination is equal to 0.938. Considering the small difference between obtained coefficients of determination, it possible to confidently determine the amount of compressive strength of polymer-modified mortars by using the semi-destructive test of "Twist-off" and utilizing linear calibration curve of Fig. 3a with the equation of y=0.195x in order to assess the compressive strength of mortars modified with the polymer of SBR. According to Fig. 3b, it is observed that the coefficients of determination and correlation are respectively equal to 0.766 and 0.875 by performing regression analysis in exponential mode between flexural strength and the results attained from the "Twist-off" test. Thus, it is possible to use the obtained results from the "Twist-off" test for converting to the flexural strength of mortars modified with the polymer of SBR, With 88% confidence, by utilizing the calibration curve of Fig. 3b and the equation of $y=0.124x^{0.545}$.

3.1.2. Obtained results from "Pull-off" test

The relation between the compressive and flexural strength of mortars and obtained results from the "Pull-off" test is illustrated in Fig. 4.

According to Fig. 4a which is about the regression analysis between compressive strength and obtained results from the "Pull-off" test, it is observed that the coefficient of determination is equal to 0.947 in linear mode. However, regarding the "research hypothesis", if the regression equation is chosen in a linear mode as y=ax and the regression analysis is performed again, then the coefficient of determination is equal to 0.944. Considering the small difference between obtained coefficients of determination, it possible to confidently determine the amount of compressive strength of polymer-modified mortars by using the semi-destructive test of "Pull-off" and utilizing linear calibration curve of Fig. 4a with the equation of y=0.063x in order to assess the compressive strength of mortars modified with the polymer of SBR. According to Fig. 4b, it is observed that the coefficients of determination and correlation are respectively equal to 0.73 and 0.85 by performing regression analysis in exponential mode between flexural strength and the results attained from the "Pull-off" test. Thus, it is possible to use the obtained results from the "Pull-off" test for converting to the flexural strength of mortars modified with the polymer of SBR, With 85% confidence, by utilizing the calibration curve of Fig. 4b and the equation of $y=0.025x^{1.72}$.

3.2. The effect of the SBR latex on the dry shrinkage of the repair mortars

In this section, the effect of the SBR latex on the dry shrinkage of cement base repair mortars was studied. For this purpose, the mortar with water-cement ratio of 0.5, and sand-cement ratio of 3 were used. Afterwards, the SBR latex was added by 10, 15 and 20% of the cement to mortars weight percentage. Fig. 5 has demonstrated the mortar shrinkage with various weight percentages of polymer and in various ages.

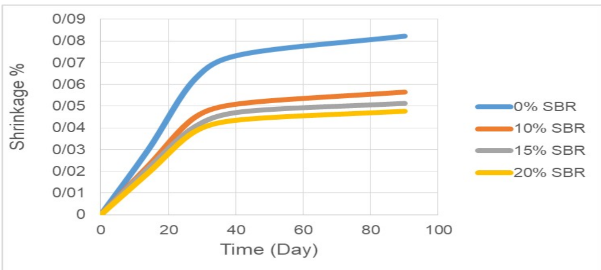


Fig. 5 - Mortar Shrinkage.

According to Fig. 5 it is observed that adding the SBR latex has decreased the mortar shrinkage. Besides, increasing the weight percentage of polymer decreases the shrinkage further so that 90-day shrinkage for the mortar consisting of 20% SBR is less than 10 and 15% SBR by 15.6 and 7%, respectively. It is obvious that adding the 10, 15, and 20% of SBR to the mortar decreases the shrinkage by 32.8%, 36.1%, and 42.1%, respectively for the polymer-modified mortars compared to the conventional mortar 14-day age. The same shrinkage decrement was observed in other ages. Different study on the effect of SBR latex had also concluded that adding polymer reduces the dry shrinkage [31]. One of the main reasons in the shrinkage decrement of the polymer-modified mortars is the sealing property of latex that prevents the humidity output from the inside of the cement matrix [32, 33].

3.3. Determining the bond strength

3.3.1. Shear bond strength obtained from the "Twist-off" test

Fig. 6 demonstrates the shear bond strength between repair mortars and the concrete substrate obtained from the "Twist-off" test. The samples were kept in the water during curing process for one week and then were got out and tested in the various ages. Fig. 6 shows that adding the SBR latex to mortar increased the shear bond strength between the repair mortar and the concrete substrate. The highest increment is observed in the mortar consisting of 15% of SBR latex and the least increment is observed in the mortar consisting of 20% of SBR latex. Adding 10% of SBR latex to the mortar increased the shear bond strength within the ages of 7, 42, and 90 days by 25.9, 115.2 and 187.3%, respectively. Also, by adding 15% of SBR latex, the adhesion increment in the mentioned ages was equal to 48.4, 155 and 246.8%, respectively. The shear bond strength increment is also observed by adding 20% of SBR latex so that the bond strength increment within the ages of 7, 42, and 90 days was equal to 42.4, 143.9 and 215.1%, compared to the polymer-free mortar, respectively.

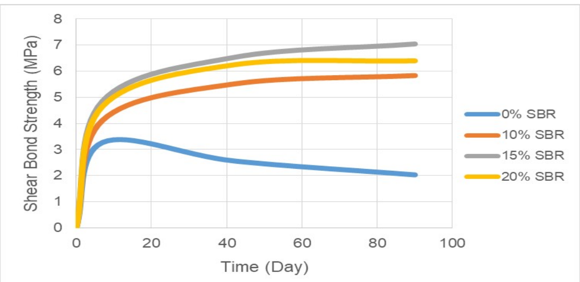


Fig. 6 - Shear bond strength.

By comparing the mortars with the various percentage of polymer, it was obvious that the shear bond strength obtained from the "Twist-off" test increased for the polymer-modified mortar consisting of 15% of SBR latex by 17.8 and 4.3% in the age of 7-day compared to the mortars consisting of 10 and 20% of SBR latex. This increment was also observed in the ages. In addition, 18.4 and 4.5% increment in the age of 42-day, 20.7 and 10.1% increment in the age of 90-day was also observed. The polymer film formation in the mortar is the reason of increasing the bond strength between the polymer-modified mortars and the concrete substrate. When the polymer and the Portland cement paste have contact with each other, they give more solidarity to the entire cement matrix through the strong covalent and ionic bonds which leads to the enhancement in the properties [34]. It was seen in the other studies that adding polymer increases the bond strength between repair mortar and the concrete substrate [35].

3.3.2. Tensile bond strength obtained from the "Pull-off" test

Fig. 7 demonstrates the tensile bond strength between repair mortars and the concrete substrate obtained from the "Pull-off" test. The samples were kept in the water during curing process for one week and then were got out and tested in the various ages.

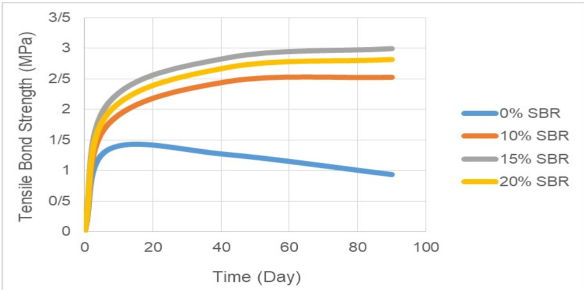


Fig. 7 - Tensile bond strength.

Fig. 7 shows that adding the SBR latex to mortar increased the tensile bond strength between the repair mortar and the concrete substrate. The highest increment is observed in the mortar consisting of 15% of SBR latex and the least increment is observed in the mortar consisting of 20% of SBR latex. Adding 10% of SBR latex to the mortar increased the tensile bond strength within the ages of 7, 42, and 90 days by 31.4, 94.8 and 170.2%, respectively. Also, by adding 15% of SBR latex, the adhesion increment in the mentioned ages was equal to 56.7, 125.7 and 220.3%, respectively. The tensile bond strength increment is also observed by adding 20% of SBR latex so that the bond strength increment within the ages of 7, 42, and 90 days was equal to 44.8, 113.2 and 201.3%, compared to the polymer-free mortar, respectively. By comparing the mortars with the various percentage of polymer, it was obvious that the tensile bond strength obtained from the "Pull-off" test increased for the polymer-modified mortar consisting of 15% of SBR latex by 19.2 and 8.2% in the age of 7-day compared to the mortars consisting of 10 and 20% of SBR latex. This increment was also observed in the ages. In addition, 15.8 and 5.8% increment in

Table 2

The compressive and flexural strengths of the mortars

	compressive strength			flexural strength		
	7 Days	42 Days	90 Days	7 Days	42 Days	90 Days
0% SBR	34.1	51.2	54.4	8.6	9.71	10.11
10% SBR	25.6	38.8	42.2	10.51	12.02	12.55
15% SBR	23.8	37.7	40.8	11.92	13.52	14.19
20% SBR	22.8	36.1	39.2	12.46	14.54	15.2

the age of 42-day, 18.5 and 6.3% increment in the age of 90-day was also observed. As mentioned in the previous section, the polymer film formation in the mortar is the reason of increasing the bond strength between the polymer-modified mortars and the concrete substrate. When the polymer and the Portland cement paste have contact with each other, they give more solidarity to the entire cement matrix through the strong covalent and ionic bonds which leads to the enhancement in the properties [34]. It was seen in the other studies that adding polymer increases the bond strength between repair mortar and the concrete substrate [35].

Fig. 8 shows the correlation between shear bond strength obtained from the “Twist-off” test and tensile bond strength obtained from the “pull-off” test.

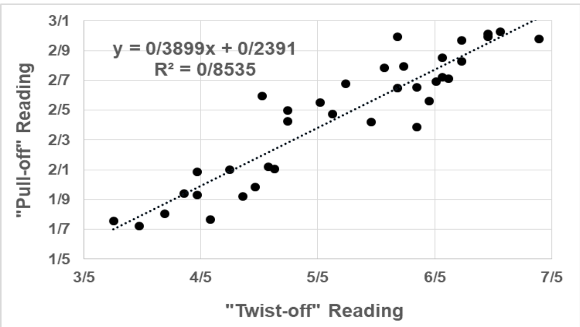


Fig. 8 - The correlation between the results of in-situ tests (MPa).

According to the Fig. 8, the determination factor of “pull-off” and “Twist-off” tests is 0.854. In addition, the correlation factor of two mentioned tests is 0.924. Considering the high correlation factor of the results of “pull-off” and “Twist-off” tests, it is possible to obtain the results of one test and consider it for the other test. Also, it is worth noting that the damages of two methods are negligible. According to the high correlation between the “Twist-off” and “pull-off” methods, the simple and cheap machine of “Twist-off” can be used instead of the expensive machine of “pull-off”.

3.4. The effect of SBR latex on the compressive and flexural strengths of the mortars

The compressive and flexural strengths of the typical mortar and the polymer-modified mortar is shown in Table 2.

It can be observed, according to Table 2 that adding the SBR latex decreases the compressive strength of the cement-based mortars. Also, increasing the polymer content leading to a further decrease of compressive strength. Adding 10, 15, and 20% of SBR latex has decreased the 7-day compressive strength of the repair mortar by 24.9, 30.2, and 33.1%, respectively. The same decrease can also be observed at the age of 42 and 90 days so that the 90-day compressive strength of modified mortars with 10, 15, and 20% SBR latex has decreased by 22.4, 25, and 27.9%, respectively. In all specimens, it is observed that over time, the compressive strength of the specimens has increased due to the more completion of the cement hydration process. One of the main reasons for the decrease in compressive strength of the polymer-modified mortar is since SBR latex has caused air bubbles in the structure of the cementitious materials; this results in more porosity in the mortar and therefore decreases the compressive strength. Also, applying the polymer in mortar postpones the hydration process and, as a result, decreases the compressive strength as well [36]. It can be observed, according to Table 2 that adding the SBR latex has increased the flexural strength of the cement-based mortar. At the age of 90-day, adding 10, 15, and 20% SBR latex to the mortar has increased the flexural strength by 24.1, 40.3, and 48.6%, respectively. At the age of 7 and 42 days, the flexural strength of the polymer-modified mortars has increased compared to typical mortar. It was mentioned in the previous studies that the use of SBR latex in mortar increases the adhesion between the aggregate and paste of the Portland cement [37].

3.5. Modeling the “twist-off” and “pull-off” semi-destructive tests

In the ABAQUS finite element software, the nonlinear behavior of the brittle materials can be defined in three various methods including brittle cracking model, smeared cracking model, and concrete damage plasticity model. The concrete damage plasticity is a model, which can be used in statistical and dynamical analysis. In this model, two main aspects of the failure mechanism are the tensile cracking and compressive crushing. In the finite element analysis, the grid type and the solution convergence are very crucial. The problem solution is converged to a single response by reducing the dimension of elements. In the “Twist-off” and “pull-off” tests, the cubic mortar part mortar is meshed using a combination of C3D8R and C3D4 elements. The main part in modeling which is under tension or pressure, was meshed by8 node cubic element and the C3D8R reduced-integral. Primarily, the convergence of solution was investigated in the grid sizes of 0.5, 1 and 2 mm, which the 1 mm element was selected. Also, the lateral parts were meshed by continuous tetragonal element with 4 nodes with the minimum size of 1 mm in the areas which were connected to the main element and maximum size of 15mm which were placed at the corners. Also, the adhesive part and the steel part were meshed with the 2 mm size of C3D8R element and 2 mm size of the element, respectively. The elements have been considered 10 mm for the steel part in the axial direction.

A mortar sample, with the compressive strength of 47.6 MPa, was used for modeling. In the finite element method used for “Twist-off” test, the maximum moment which caused the fracture was 177.5 Nm. According to Fig. 9a, the first cracks was occurred in the sample in the moment of 49.8 Nm in its sides and from the corners which were under the maximum moment. According to Fig. 9b, the moment increases up to 177 Nm along with the rotation increment that the cracks reach each other in this time and the destruction.

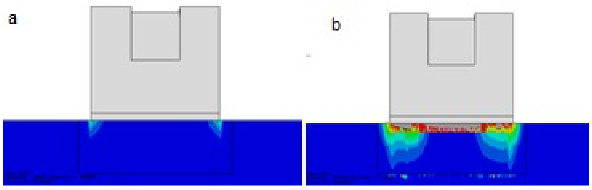


Fig. 9 - The “Twist-off” test; a) The start moment of the cracks, b) Failure moment.

In the “pull-off” test, according to Fig. 10a, the primal cracks start where the metal cylinder is connected to the mortar when the applied force is 2448 N. The crack grew significantly in the 3814 N. Finally, according to Fig. 10b, the model reaches the critical force of 4555 N and after that, the crack grew and the process force reduces until the model reaches the complete fracture.

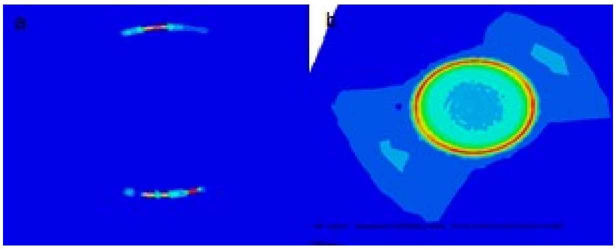


Fig. 10 - The “pull-off” test; a) The start moment of the cracks, b) The moment of the core fracture.

By comparing the results of modeling and the experimental results it is obvious that the experimental results have a high congruence with the results obtained from the finite element method. In the “pull-off” test, the ultimate force applied to the core was obtained 4500 N which is very close to the force obtained from the finite element method (4555 N). Also, in the “Twist-off” test, the experimental and finite element moments are equal to 186 and 177.5 Nm respectively that have a negligible difference.

4. Conclusion

- According to the high intensity of correlation between the results obtained from the semi-destructive tests with compressive and flexural strengths of the mortar, the above tests can be used for evaluating the in-situ strength of the polymer-modified mortars.
- According to the high correlation between the "Twist-off” and "Pull-off" methods, the simple and inexpensive “Twist-off" machine can be used instead of the expensive "Pull-off" machine.
- The results of finite element analysis by ABAQUS software have a high correlation with the results obtained from the experimental, which shows the accuracy of semi-destructive tests in evaluating the strength of mortars.
- Adding the SBR latex increases the shear and tensile adhesion strength between the repair mortar and concrete substrate in which the highest increase is related to the 15% latex to the cement weight.
- Polymer-modified mortars have a less compressive strength compared to cement-based typical mortars; therefore, the use of these mortars is not recommended in places where the compressive strength of the mortar is essential.
- Adding the SBR latex increases the flexural strength of the mortars so that the flexural strength of the mortar, including 20% polymer at the age of 7, 42, and 90 days is 44.9, 49.7, and 50.3% mare than typical mortar, respectively.

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