EVALUATION OF SHEAR BOND STRENGTH BETWEEN REPAIR MATERIALS AND SUBSTRATE CONCRETE

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Abstract— Bond tests between repair materials and substrate concrete have been developed for several specific applications. Till now there is no consensus among practitioners for evaluating the bond strength under a shear state of stress that is commonly encountered in concrete structures. It is simple to carry out tension bond test in situ or in laboratory than shear bond test. The main aim of this work is to try to find out correlations between tensions and shear bond tests. Experimental work was carried out including casting thirty six concrete slabs specimens with dimension 500*500*200 mm overlaid with different types of repair materials. Concrete slab specimens were prepared using three different grades of substrate concrete (15, 25 and 35 N/mm^2), three different types of overlaid repair materials, three different types of surface bonding agents, and two different interface roughness methods. One hundred and eight locations on prepared slabs were tested in tension. One hundred and eight specimens were drilled and tested in direct shear. Test results show strong correlation between both tension and shear bond strength between repair materials and substrate concrete. Experimental relations between tension and shear bond strength were estimated.

The main aim of this research is to evaluate the tension and the shear bond strength between substrate concrete and overlay repair materials, and to find correlations between shear bond strength and tension bond strength. Several parameters were adapted to evaluate the bond strength.

1.1 INTRODUCTION

Concrete structures are usually repaired and/or strengthened by adding new layer. Concrete jacketing is a wide spread techniques where beams and column, partially or totally, involved by a new concrete layer. Bridge decks and building slabs strengthened by increasing their thickness is another example of this type of intervention. For the given example, the bond strength at the interface between concrete layers cast at different times is Important to ensure a monolithic behavior for service ability limit state and ultimate limit state.

The interfacial layer between old and new concrete usually has different aggregate/cement contents, w/c ratio, and temperature evolution during the curing period compared to the other sides of old construction material and new rehabilitation material [11]

An experimental study with the objective of quantifying the influence of the application of a bonding agent on the bond strength between two concrete layers with different ages. The selected bonding agent was a commercial, widely used, two component epoxy resin. The methods adopted to increase the roughness of the substrate surface, before the application of the bonding agent, were those most commonly used in practice. [8]

According to Garbacz et al. the adhesion in the repair system depends on the surface roughness of the concrete substrate, the presence of micro-cracks and the properties of the materials to be used for the repair. The authors state the increasing necessity of using a bond coat as the violence of surface treatment increases. Cleland and Long concluded that the principal function of a bonding agent is to develop a bonding bridge between the repairing material and the concrete substrate.[2&7]

In terms of the characteristics of the bonding agent, Emmons states that it should be easily absorbed by the pore structure of the substrate and must be compatible with both the substrate and the repairing material. This author indicates three main types of bonding agents that are frequently used: epoxies, latex and polypropylene fibers.

Bond strength can be expressed by shear resistance and tensile resistance, which can better state the stress subjected to the structure in the field, in many cases the stress in the field is a shear type, but from the measure of point of view tensile strength for bonding in structural works is easier.

The direct shear test is the simplest bond test to assess the shear strength between two materials. This test can be performed with a single (Li et al., 1997) or a double shear plan (Chen et al., 1995). [4&6]

Silfwerbrand (2003) [9&10] showed an average ratio (Shear bond/ tensile bond) around 2.4 between tests' results. In Japan Sato (1989) informed the ratio of 1.50. This is related to several factors which would possess higher influence.

Bond tests between repair materials and substrate concrete have been developed for several specific applications. Till now there is no consensus among practitioners for evaluating the bond strength under a shear state of stress that is commonly encountered in concrete structures.

1.2 OBJECTIVE

The main objective of this research work is to study evaluation of tensile and shear bond strength using pull off test &direct shear test taking into consideration the method of interface treatment, and study the correlations between tensile and shear bond strength

Three values of concrete cover were considered; 20mm, 35mm and 50mm. Three values of external chloride concentrations were considered 1%, 3% and 5%.

1.3 MATERIALS

1.3.1 Concrete and concrete materials

The constituent materials were CEM I 42.5 N Portland cement, fine aggregate, coarse aggregate, mixing water (tap water) and admixture. The cement satisfied the Egyptian Standard Specification ESS 4756-1 /2007.The chemical physical and mechanical properties of the use cement are given in table I and II.

Table I: Physical and Mechanical properties of the used cement and Chemical Composition

Mechanical Properties		Results	Standard limits
Compressive Strength (N/mm^2)	Early (2days)	21.6 N/mm^2	≥10 N/mm^2
	Standard (28 days)	57.3 N/mm^2	≥42.5 N/mm^2
Physical Properties		Results	Standard limits
Initial setting time		80 minutes	≥ 60 minutes
Chemical Composition %			
SiO_2		21.00	
AL_2O_3		3.40	
Fe_2O_3		5.00	
Ca O		63.00	
Na_2O		0.10	

Table II: Properties of Fine and Coarse Aggregates

Property	Fine Agg.	Coarse Agg.
Specific gravity	2.674	2.681
Unit weight (t/m^3)	1.53	1.58
Crushing value (Los Anglos)	---	23.6%
% Fine materials (by volume)	2.90	4.00
% Absorption	---	1.90

Table III: Mix proportions and measured properties of substrate concrete

Mix designation	Cement (kg)	Sand (Kg)	Coarse Agg. (Kg)	Water (Liter)
M35	400	720	1080	200
M25	350	760	1135	175
M15	200	850	1270	140

Table V: Mix proportions and measured properties of overlay concrete

Mix designation	Cement (kg)	Sand (Kg)	Coarse Agg. (Kg)	Water (Liter)
M35	400	720	1080	200

1.3.2 Repair Material

The bonding materials used in this study are, Epoxy bonding, Modified cement coat (Latex), and Cementitious mortar. The details of binder materials and its technical Specifications are shown in Table IV.

Table IV: The details of binder materials and its technical Specifications

	Epoxy Adhesive		Latex Adhesive		Polyprop-ylene Fiber
	Type I	Type II	Type I	Type II	
Color	Light Grey	Light off-white	White	White	White
Density	1.4 kg/l	1.49 kg/l	1.01 kg/l	1.02 kg/l	0.91 g/cm^3
Spec.	ASTM C881	ASTM C882	ASTM C882	ASTM C631	-----
Comp. strength N/mm^2	50-60	-------	35	-------	--------

1.4 TEST PROGRAM AND SPECIMENS PREPARATION

1.4.1 Test Program

The experimental program consists of thirty six slabs specimens, the slabs consists of substrate concrete and repair concrete. The substrate concrete was selected from different strengths of f_{cu}=35, f_{cu}=25 and f_{cu}=15 Mpa), however the repair concrete was high strength concrete with f_{cu}=35 Mpa, In order to study the effect variation of concrete strength on old-new concrete bond strength. The three groups for old concrete /new concrete are made 15/35 Mpa, 25/35 Mpa and 35/35 Mpa. The interface between old and new concrete was roughened in different ways, mechanical and acid etching roughness.

Pull-off test was used to measure the effectiveness of repair materials in tension bond, while shear bond strength was measured using Direct Shear test. Figures (1-a, 1-b) shows the preparing of the test specimens.

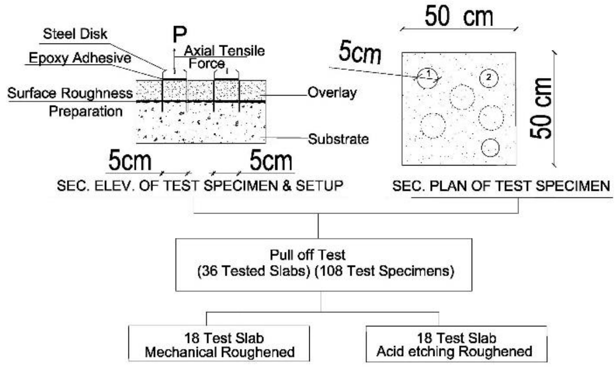

Figure (1-a): Diagrammatic sketch for the experimental program.

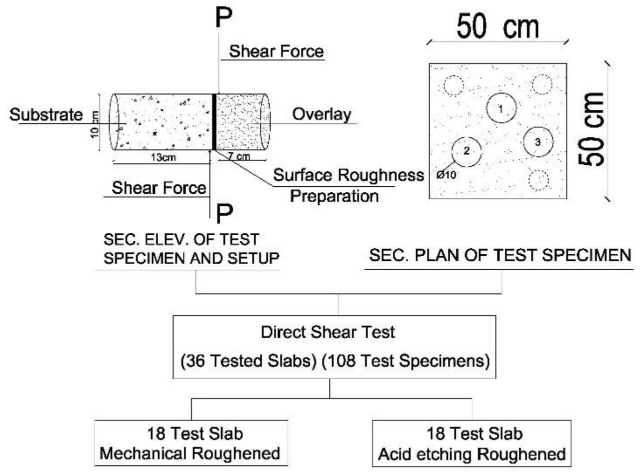

Figure (1-b): Diagrammatic sketch for the experimental program

Dimension of 500*500*200 mm for concrete test specimens were cast to investigate the tensile bond strength and shear bond strength one of them 130 mm substrate concrete and the other one is 70 mm repair concrete.

The pull-off specimens were drilled 70 mm below the substrate concrete interface. In these specimens start loading till reaches the failure, the test tension load was applied at the center of specimens as shown figure (1). The Direct shear test was carried out on cylindrical specimens of 100 mm diameter*200 mm high. In the shear test, a shear force was applied on the bond surface as shown figure (1). For tension test, three specimens were used and the mean value was considered and for shear test, three specimens were used and the mean value was considered. This study was carried out on 108 cylinder specimens test in tension, and 108 cylinder specimens test in shear.

1.4.2 Specimens Preparation

The different concrete mixes were used for the concrete in the substrate portion of all specimens. Wooden molds were prepared, marked at height 120 mm in the interior face from its base to adjust the thickness of the substrate. Mixing of the concrete components was carried out in the laboratory by using a rotary mixer and the concrete was placed in lubricated wooden forms. After the mark level of the molds had been filled of concrete and compacted, the surfaces of concrete were leveled and they were kept in the laboratory conditions, Figure (2). After 24 hours the specimens were removed from the forms and after cleaning they were cured by water for 7 days by use wet burlap, specimens were left to dry to prepare the surface for roughness, then the repairing surface of some of specimens were roughened using mechanical roughening for 18 specimens to obtain 5 mm depth roughness, and 18 remaining specimens for acid etching to obtain 2-3mm depth roughness, Figure (3).

The specimens were kept to dry for one week prior to applying the bonding material, the interface surface was cleaned from any extra dust or loose particles and grease. The bonding materials of the different epoxies, modified cement and cementitious mortars prepared for application. Epoxy was prepared by adding the hardener to the resin in ratio 2:1 and mixed until obtaining uniform color, Latex, water, cement and fine sand were prepared according to the technical product data sheets, and cementitious mortars were used Polypropylene fiber was mixed with the over lay.

A stiff brush was then used to distribute the epoxy and latex materials on the interface surface. Thereafter, the specimens were left for about 30 minute before placing in the lubricated molds once, again and the repairing concretes were cast and compacted with tamping and vibrator. The specimens were covered with wet burlap and left 24 hours in the laboratory. The composite specimens were demolded and cured in water for additional 7 days until testing. In parallel, six continuous specimens of each mix were cast for the purpose of comparison, 3 samples cured for 7 days and another 3 sample cured for 28 days.

Figure (2) Fabrication of sample substrate concrete and repair concrete

a)Acid Etching Roughness b)Mechanical Roughness

Figure (3) Roughness Surface preparation for substrate concrete

1.5 Test Result and Discussion

In this research, all specimens either composite were tested after 28 days age of repair concrete casting. Each group of specimens as identified with two parts, the first part refer to the concrete strength of the new /old concrete (35MPa/35MPa), (35MPa/25MPa) and (35Mpa/15Mpa) and the interface surface roughness (acid etching roughness and mechanical roughness), and the second parts refers to type of bonding agent materials (Epoxy (I, II), Latex (I, II) and polypropylene fiber).

1.5.1 Mode of Failure

The mode of failure is characterized by the location of the failure in the specimens: either along the interface surface (bond failure) or in concrete in any side of the bond surface (non-bond failure). Bond failure occurred in all of specimens with identical high strength of concrete substrate and repair concrete (35/35).On the other hand, non-bond failure depends on the compressive strength of the weakest concrete.(35/15).However, for moderate strength repair concrete(35/25) a few specimens failed partially in the repair concrete and the bond surface material ,Fig (4).

It was also noted that the specimens of cohesive failures increased with the interface surface.

Figure (4): Specimens after failure

1.5.2 Pull-off Test

Pull-off test with adopting three different factors quality of concrete, bonding agent type and roughness the interface of substrate concrete, were used to assess the effect of factors of bond strength. However, to allow comparison of the results with different factors and different modes of failure, an equivalent tensile strength was calculated considering the sectional area in this test. The average value of tension strength of continuous bond specimens, i.e, specimens were determined from the samples that were cast into the slabs, are present in Figure (5-9).

The tension bond strength was calculated by the following equation:

$$f_t = \frac{P}{\frac{\pi}{4}d^2} \quad (N/mm^2)$$

Where f_t= pull-off bond strength, P= the applied tensile force, d=diameter of test specimen.

Figure (5-9) show the average of the bond strength at each parameter and affect it on the bond strength.

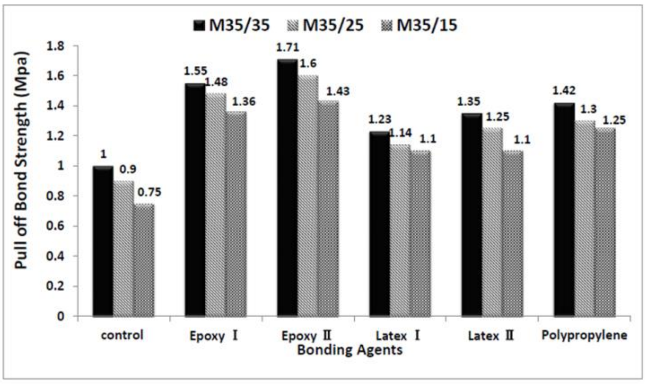

Figure (5-a)

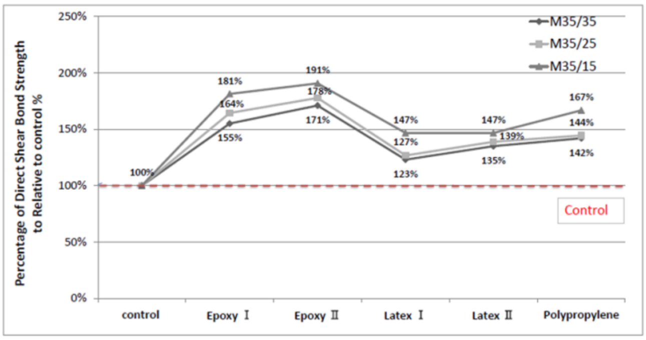

Figure (5-b)

Figure (5-a, b): The mean pull-off bond strength for different bonding agents, Acid etching roughness, and quality concrete of substrate.

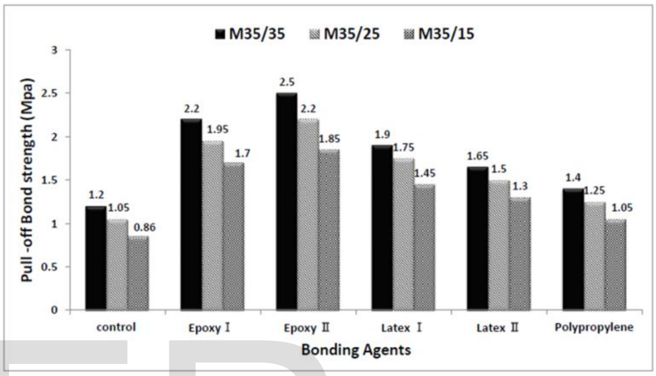

Figure (6-a)

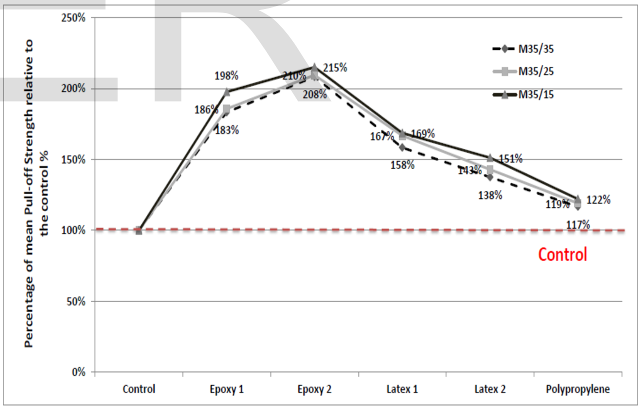

Figure (6-b)

Figure (6-a, b): The mean pull-off bond strength for different bonding agents, Mechanical roughness, and quality concrete of substrate

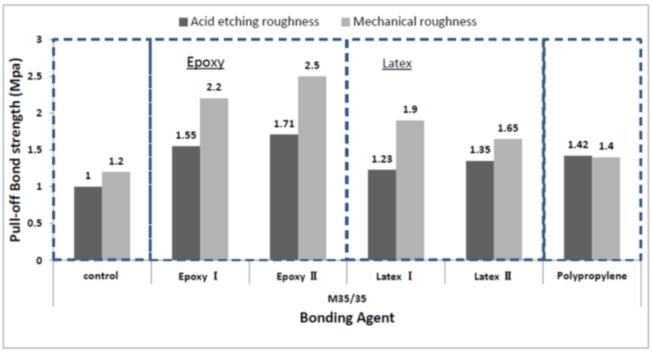

Figure 7-a: The mean pull-off bond strength vs. the surface with different agent and quality substrate concrete (M35/35)

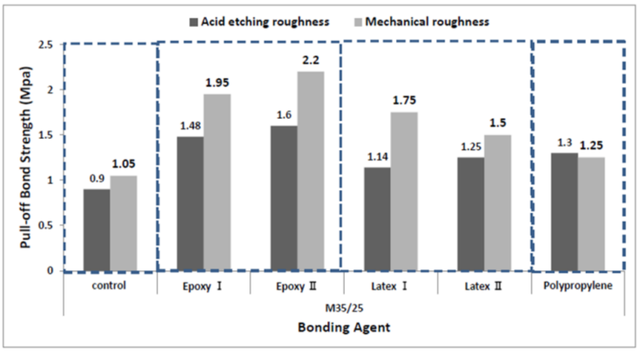

Figure 7-b: The mean pull-off bond strength vs. the surface with different agent and quality substrate concrete (M35/25)

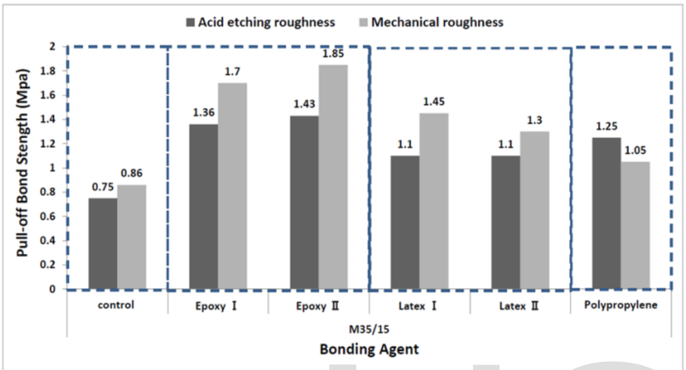

Figure 7-c: The mean pull-off bond strength vs. the surface with different agent and quality substrate concrete (M35/15)

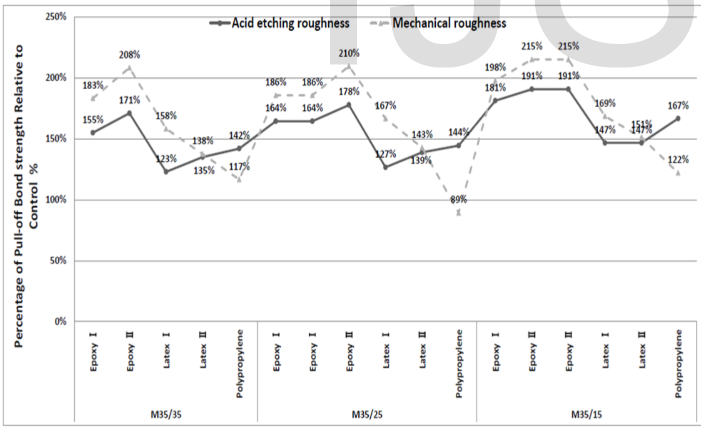

Figure 7-d: The percentage of mean pull-off strength for different bonding agents, mechanical and acid etching roughened surface, and different quality concrete

Figure (7) (a, b, c &d) the mean pull-off bond strength vs. the surface

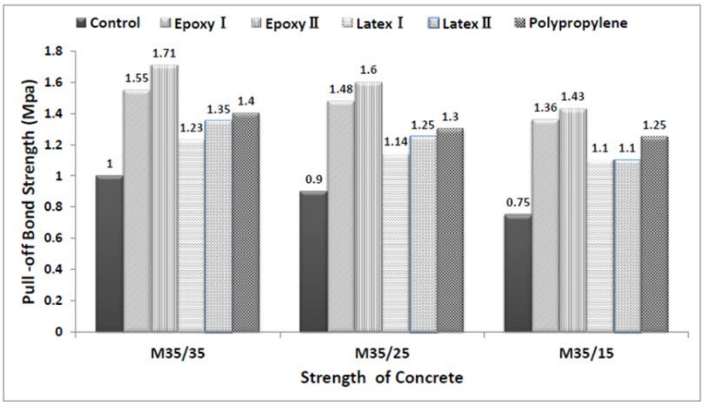

Figure (8-a)

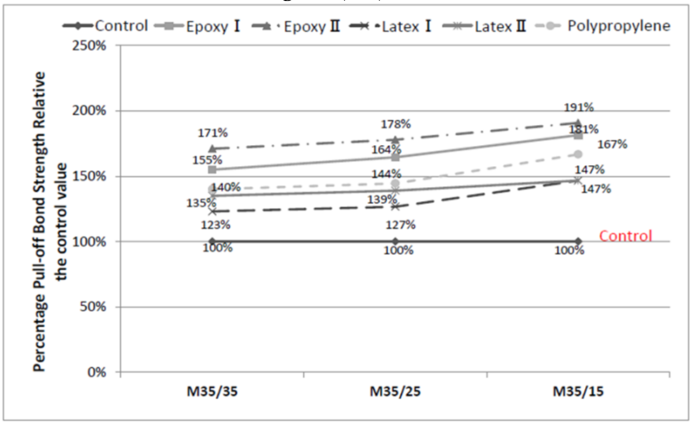

Figure (8-b)

Figure (8-a, b) The mean pull-off bond strength for different quality concrete, different adhesive materials and acid etching roughness

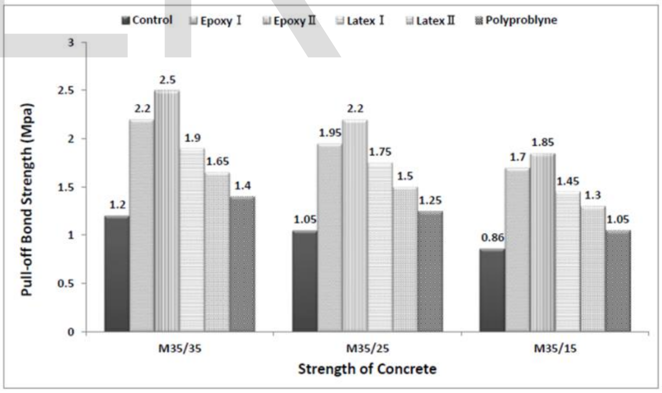

Figure (9-a)

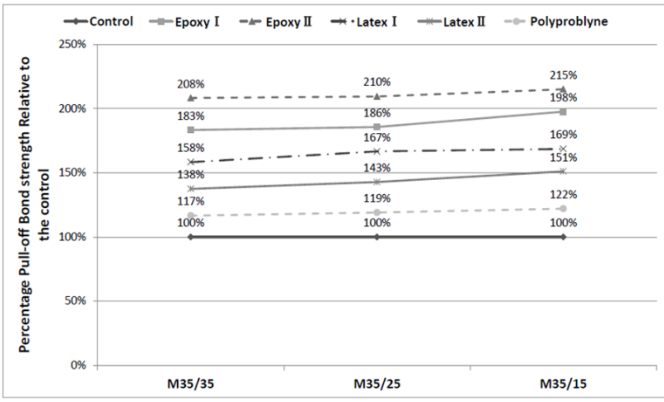

Figure (9-b)

Figure (9-a, b) The mean pull-off bond strength for different quality concrete, different adhesive materials and mechanical roughness)

In general, Epoxy type showed relatively the highest value followed cementitious mortar (Latex) then the Polypropylene fiber showed less values is as cast (with mechanical roughness)specimens. Also, Epoxy type showed relatively the highest value followed Polypropylene fiber then Latex showed less value is as cast (with acid roughness).The difference between the bond strength of specimens with different agent bonding type relatively vanished when the difference in concrete stiffness/ strength of substrate and the repair concrete was reduced and with rough interface surface.

For the concrete quality, the bond strength produced was reasonable and ensured higher bond strength especially when the strength of repair concrete and the concrete substrate were identical and with roughened interface surface (M35/35), compared to another specimens for different quality substrate concrete(M35/25 and M35/15). The bond strength of the interface increased with the surface roughness, as expected.

The variation of bond strength due to the effect of mechanical roughness compared to the effect of the acid etching roughness is shown in figure (5-9). From figures (5-9) it can be observed that the tension bond strength increases for different agent bond types and concrete quality, with the surface roughness. For specimens with mechanical roughness the tension bond strength increased specially with epoxy material, while decreases gradually with latex and polypropylene fiber, but in acid etching roughness observes the tension bond strength with polypropylene fiber and decrease with epoxy and latex.

1.5.3 Direct Shear Test:

The bond strength in this test was calculated by dividing the maximum load at failure by the surface bond area; that is equal to 100 mm*200 mm. The average shear bond strength (f_{sh}) of monolithic specimens is recorded in Figures (10-14).

Figures (10-14) shows the shear bond strength of different bonding agent materials and the surface roughness method. Main observation that can be noted from these results: the first is shear strength of epoxy material as bonding agent material by round (130-150%) in average for mechanical roughness and polypropylene fiber the highest (92-100%) in average for acid etching roughness.

With the use of mechanical roughness interface surface, the shear bond strength significantly increased for example, with about (113-150%) for epoxy, (67-100) for latex and (23-41%) for polypropylene fiber, while acid roughness case the propylene fiber the highest. With the quality control the strength of repair concrete and the concrete substrate were identical and with roughened interface surface (M35/35), compared to another specimens for different quality substrate concrete(M35/25 and M35/15).

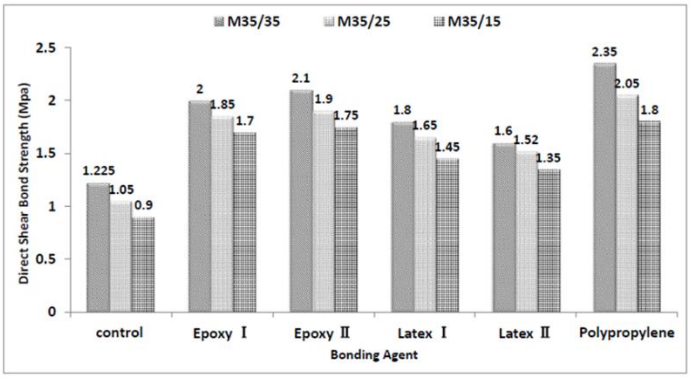

Figure (10-a)

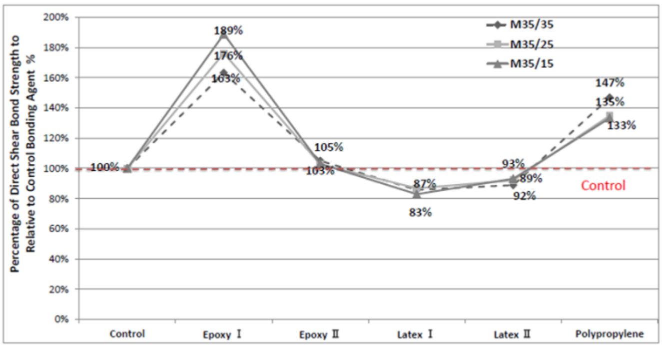

Figure (10-b)

Figure (10-a, b) The mean direct shear bond strength for different bonding agents, Acid etching roughness, and quality concrete of substrate

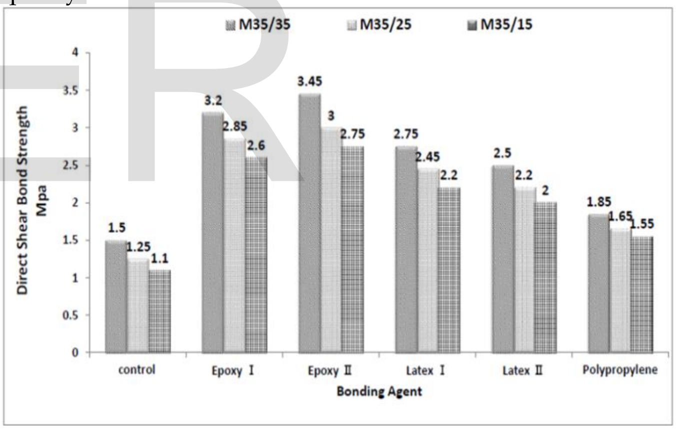

Figure (11-a)

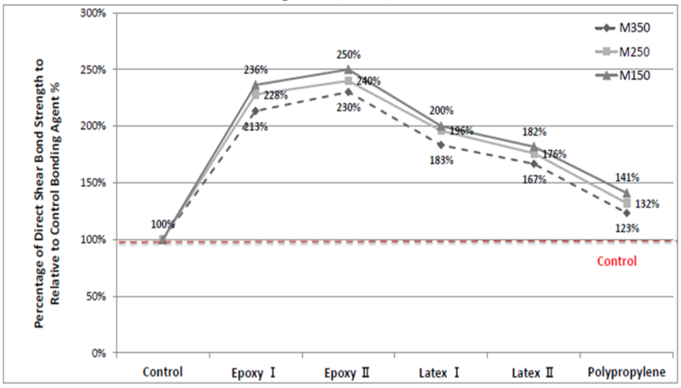

Figure (11-b)

Figure (11-a, b) The mean direct shear bond strength for different bonding agents, Mechanical roughness, and quality concrete of substrate.

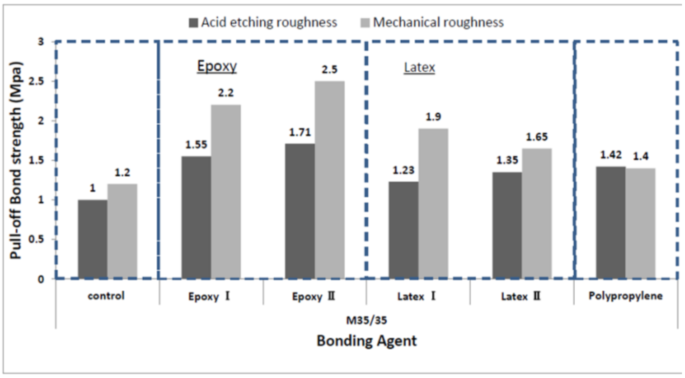

Figure (12-a): The mean direct shear bond strength vs. the surface with different agent and quality substrate concrete (M35/35)

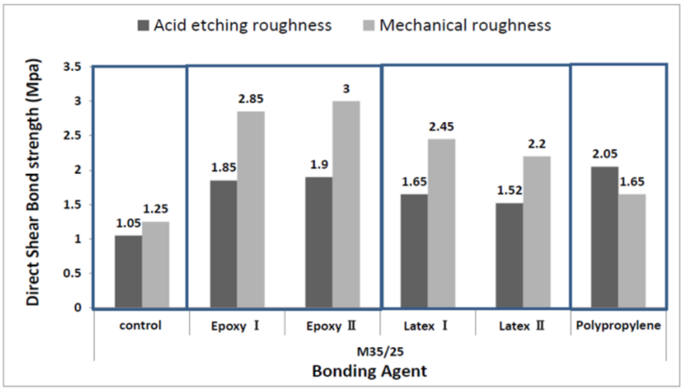

Figure (12-b): The mean direct shear bond strength vs. the surface with different agent and quality substrate concrete (M35/25)

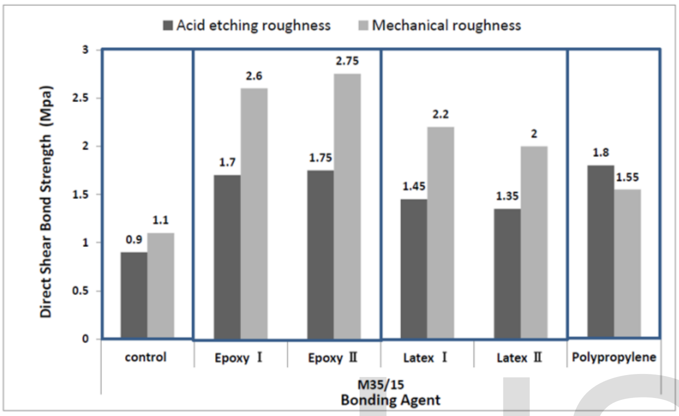

Figure (12-c): The mean direct shear bond strength vs. the surface with different agent and quality substrate concrete (M35/15)

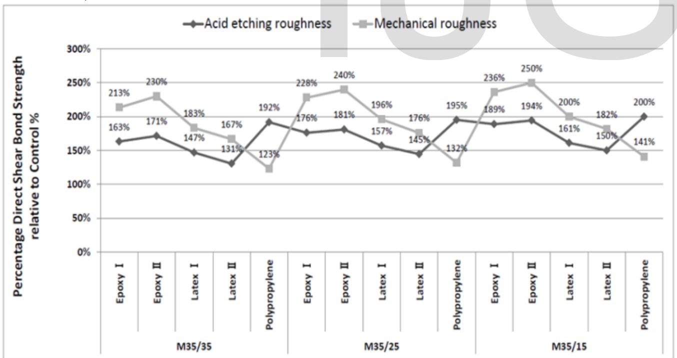

Figure (12-d): The percentage of mean direct shear bond strength for different bonding agents, mechanical and acid etching roughened surface and different quality concrete.

Figure (12) (a, b, c &d): The mean Direct Shear bond strength vs. the surface

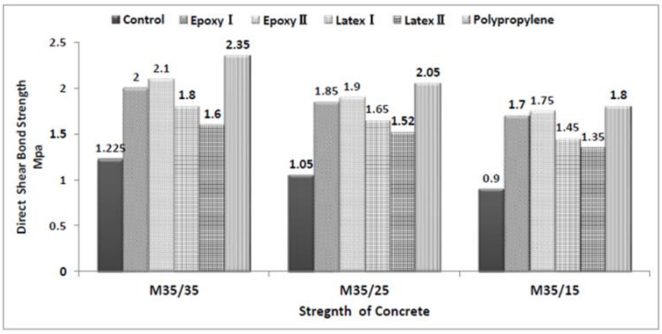

Figure (13-a)

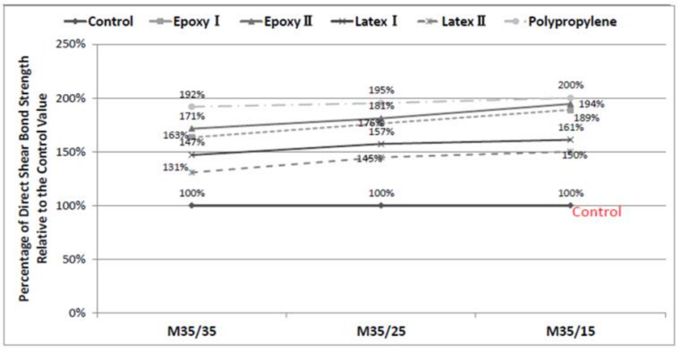

Figure (13-b)

Figure (13-a, b): The mean Direct Shear bond strength for different quality concrete, different adhesive materials and acid etching roughness.

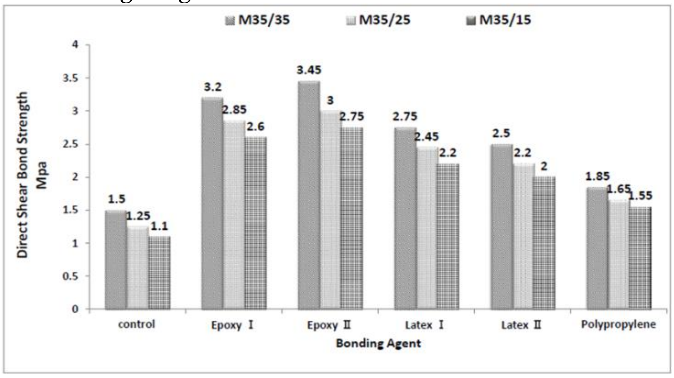

Figure (14-a)

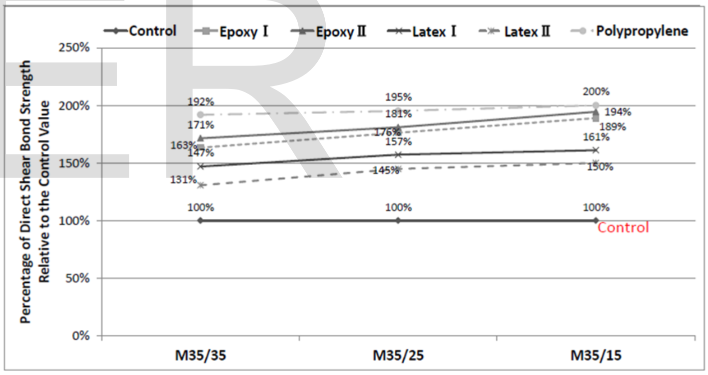

Figure (14-b)

Figure (14-a, b): The mean Direct Shear bond strength for different quality concrete, different adhesive materials and mechanical roughness.

1.5.4 Correlation between Shear Bond Strength and Tension Bond Strength

Figures (15-20) shows a correlation between the shear bond strength and tension bond strength to evaluate shear bond strength by different three parameters.

Linear regression analyses of data were carried out to estimate experimental relationships between the tensile bond strength and the shear bond strength to substrate concrete roughened.

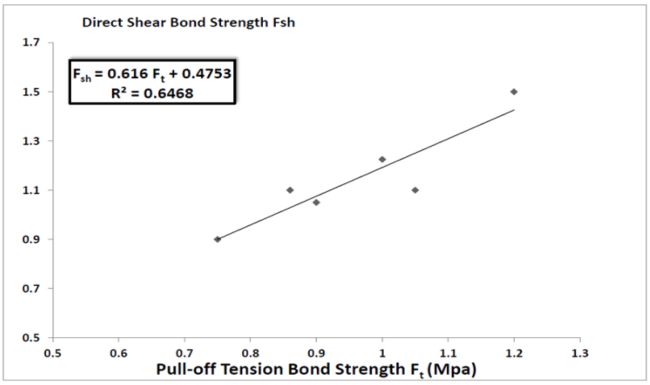

Figure (15): The correlation between Direct Shear Bond Strength and Pull-off Tensile Bond Strength. Without Bonding Agent

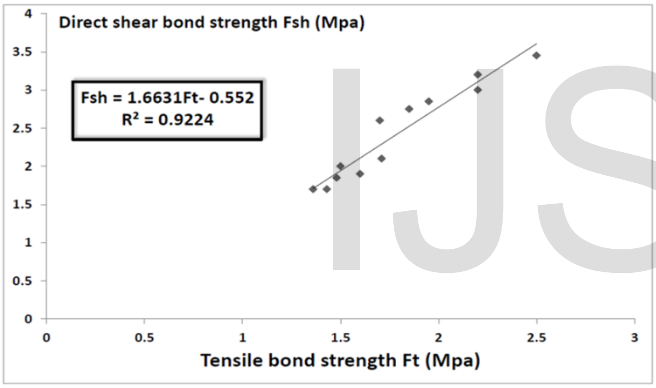

Figure (16): The correlation between Direct Shear Bond Strength and Pull-off Tensile Bond Strength with Bonding Agent Epoxy.

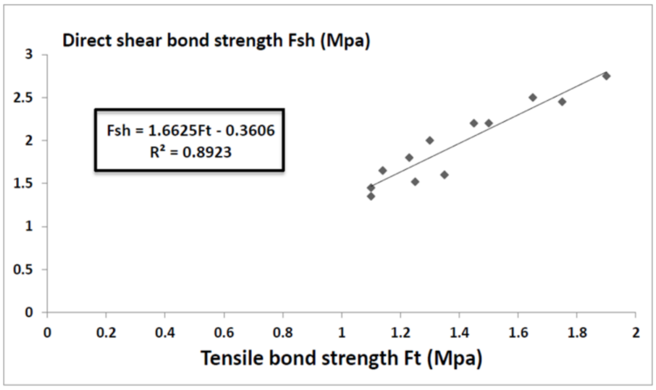

Figure (17): The correlation between Direct Shear Bond Strength and Pull-off Tensile Bond Strength with Bonding Agent Latex.

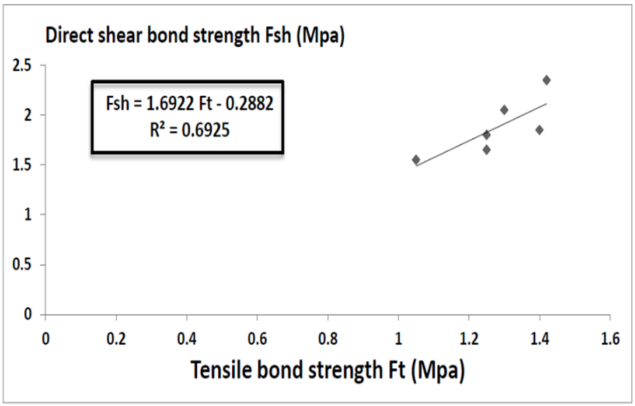

Figure (18): the correlation between Direct Shear Bond Strength and Pull-off Tensile Bond Strength. With adding polypropylene fiber

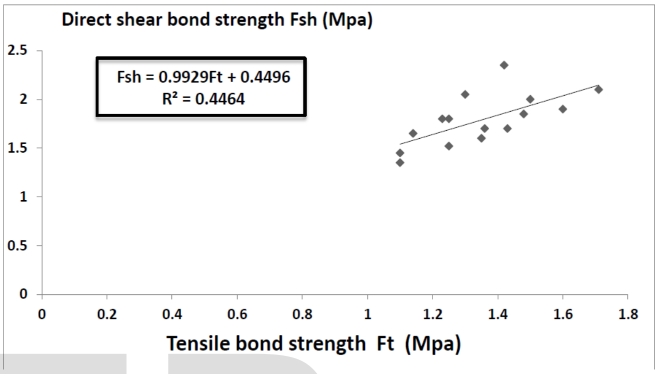

Figure (19): The correlation between Direct Shear Bond Strength and Pull-off Tensile Bond Strength with acid etching roughness.

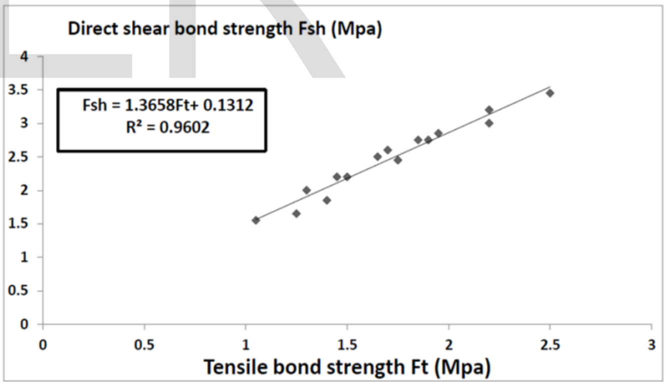

Figure (20): The correlation between Direct Shear Bond Strength and Pull-off Tensile Bond Strength with acid etching roughness

Last figure (15-20) shows that both tensile bond strength and shear bond strength are strongly correlated. This means that, if one of them is known the second can be estimated. This linear relationship can help in the estimation of the shear bond strength, as the tensile bond strength can be evaluated in situ by carrying out the pull-off test, which is a reliable test of evaluation the in situ tensile bond strength.

1.6 CONCLUSIONS

Based on the experimental and precise studies carried out in this research work, the main following points may be concluded:

1. Applying a fresh concrete layer on a hardened mechanically roughened produce pull-off bond strength (1.21, 1.05 and 0.86) for quality concrete (f_{cu}=35, f_{cu}=25 and f_{cu}=15) respectively, and in case of acid etching roughened produce pull-off bond strength (0.90, 0.80 and 0.70) for quality concrete (f_{cu}=35, f_{cu}=25 and f_{cu}=15) respectively with no bonding Agent.
2. Applying a fresh concrete layer on a hardened mechanically roughened produce direct shear bond strength (1.40, 1.32 and 1.22) for quality concrete (f_{cu}=35, f_{cu}=25 and f_{cu}=15) respectively, and in case of acid etching roughened produce direct strength (1.20, 1.05 and 0.90) for quality concrete (f_{cu}=35, f_{cu}=25 and f_{cu}=15) respectively with no bonding Agent.
3. Bonding coat significantly improved the bond strength and increased evaluate about 80% higher than the corresponding non-adhesive control specimens for tensile bond strength and 150% for shear bond strength.
4. Bond strength was significantly affected by the change of the surface roughening method from mechanical to acid etching method. The acid etching method can be used for the substrate surface cleaning, followed by mechanical method depending on site condition.
5. The direct shear bond strength is a moderate correlated with pull-off tensile bond strength without bond strength, coefficient of correlation R^2 equal 0.6468, the following linear regression relationships might be estimated :

   $$\mathbf{f_{sh} = 0.616\, f_t + 0.4753}$$

6. The direct shear bond strength is a strongly correlated with pull-off tensile bond strength with result all parameters, coefficient of correlation R^2 equal 0.8854, the following linear regression relationships might be estimated:

   $$\mathbf{f_{sh} = 1.4563\, f_t - 0.0913}$$

7. The direct shear bond strength is a strongly correlated with pull-off tensile bond strength with epoxy bonding agent, coefficient of correlation R^2 equal 0.9224, the following linear regression relationships might be estimated

   $$\mathbf{f_{sh} = 1.6631\, f_t - 0.5520}$$

8. The direct shear bond strength is a strongly correlated with pull-off tensile bond strength with latex bonding agent, coefficient of correlation R^2 equal 0.8923, the following linear regression relationships might be estimated:

   $$f_{sh} = 1.6631\, f_t - 0.5520$$

9. The direct shear bond strength is a moderately correlated with pull-off tensile bond strength with latex bonding agent, coefficient of correlation R^2 equal 0.7426, the following linear regression relationships might be estimated:

   $$f_{sh} = 1.6625\, f_t - 0.3606$$

10. The direct shear bond strength is a weak correlated with pull-off tensile bond strength with latex bonding agent, coefficient of correlation R^2 equal 0.4464, the following linear regression relationships might be estimated:

    $$\mathbf{f_{sh} = 0.9929\, f_t + 0.4496}$$

11. The direct shear bond strength is a strongly correlated with pull-off tensile bond strength with mechanical roughness, coefficient of correlation R^2 equal 0.9602. The following linear regression relationships might be estimated:

    $$f_{sh} = 1.3658\, f_t + 0.1312$$

12. An average ratio (shear bond/tensile bond) around (1.2 to 1.6) between tested results.

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