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Evaluation of Shear Bond Strength between Repair Materials and Substrate Concrete

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ملخص
حدث تطور فى إختبارات التماسك بين مواد الترميم والخرسانة الأساسية فى عديد من التطبيقات وحتى الآن لا توجد آلية محددة لتقييم قوى التماسك فى حالة القص وهى الشائعة فى المنشآت الخرسانية. من السهل إجراء إختبار التماسك بالشد فى الموقع أو فى المعمل وذلك بالمقارنة بإختبار التماسك بالقص. الهدف الرئيسى من هذا البحث هو محاولة إيجاد إرتباط بين نتائج إختبارات التماسك بالشد والقص. يتضمن البرنامج العملى صب ستة وثلاثون بلاطة خرسانية بأبعاد 500*500*200 مم تم صب أنواع مختلفة من مواد الترميم أعلاها. البلاطات الخرسانية تم تجهيزها وإعدادها بإستخدام ثلاثة رتب مختلفة للخرسانة الأساسية (150، 250، 350 كجم/سم2) وثلاثة أنواع مختلفة من مواد الترميم وثلاثة أنواع مختلفة من مواد تحسين التماسك بين الخرسانة الأساسية ومواد الترميم وطريقتين مختلفتين لتخشين سطح الخرسانة الأساسية. مائة وثمانية موضع بالبلاطات الخرسانية تم إختبارها فى الشد وتم إستخراج مائة وثمانية عينة من قلب البلاطات الخرسانية وإختبار فى القص. أظهرت نتائج الإختبارات وجود إرتباط قوى بين نتائج إختبارات التماسك بالشد والتماسك بالقص بين مواد الترميم والخرسانة الأساسية مما مكننا من أستنباط علاقات تجريبية تساعد على تقييم قيمة مقاومة التماسك بالقص وذلك بمعرفة قيمة مقاومة التماسك بالشد.

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 tension 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 (150, 250, 350 kg/cm2), 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.

Keywords
Bond strength, Tensile strength, Shear strength, Bonding materials, Surface roughness.

1. Introduction
Concrete structures are usually repaired and/ or strengthened by adding a new concrete layer. Concrete jacketing is a wide spread technique where beams and columns, 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.

Bonded concrete overlay is a viable option to increase structural capacity and/or improve ability of concrete structural. With property mismatch of new overlay concrete to old concrete however, bonded concrete overlays may lead to early age failure and a shortened service life. To better understand bond mechanism at the interface between new and old concrete surfaces, it is essential to measure bond strength at the interfacial layer and to investigate affect parameters of its properties.

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.

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.

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.

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 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.

2. Scope

This paper presents and analyses the results of an experiment research program aiming 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.

3. Study Parameter

Three experiment parameters were investigated to evaluate shear bond strength and tension bond strength, including bonding agent, quality of substrate and interface of treatment (surface roughness).

Three different types of bonding agents (Epoxy bonding, Modified cement coat (Latex), and Cementitious mortar) were chosen to study their effects on bonding strength.

The compressive strength of substrate concrete with lower w/c ratio results in higher compressive strength. (Mindess at al.2003) But shear bond strength at the interface is affected by the material properties of both new and old concrete. Controversies still exist on how w/c ratio in old concrete affects shear bond strength. In order to find how the shear strength affected by w/c ratio of the old concrete, three different w/c ratios were chosen for the experiments (fcu=35Mpa, fcu=25Mpa, and fcu=15 Mpa).

The interface of treatment was to study its effect on bonding strength, two different method were chosen for experiments (mechanical method and acid etching method)

4. Materials and Mix Proportions

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.

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

Mechanical Properties		**Results**	**Standard limits**
Compressive Strength (N/mm^2)	Early(2 days)	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		3.4	
Fe_2O_3		5.00	
Ca O		63.00	
Na_2O		0.10	
Mg O		1.00	

In this research program, the fine aggregate natural sand 4.75mm maximum particle size, the specific gravity and bulk density of sand 2.6 and 1635 kg/m3 respectively. The coarse aggregate was crushed stone with maximum aggregate size of 10 mm. The grading of the used sand and crushed stone was satisfied by the ESS no.1109/2002.
The mixing water used was clean tap potable water, and adding admixture type G superpalsticizer.to reduce the high rang water in mixing

The proportions of the concrete of the substrate concrete mix are given in to table Ⅱ and repair concrete mix are given in table Ⅲ

Table Ⅱ Mix proportions and measured properties of substrate concrete

Mix designation	Cement Content	Sand Content	Gravel Content	Water Content	Admixture
M350	400	720	1080	200	1% Cement weight
M250	350	760	1135	175	
M150	200	850	1270	140	

Table Ⅲ Mix proportions and measured properties of repair concrete

Mix designation	Cement Content	Sand Content	Gravel Content	Water Content	Admixture
M350	400	720	1080	200	1% Cement weight

The mechanical properties of the concrete of the substrate concrete and repair concrete mix are given in table Ⅳ

Table Ⅳ mechanical properties of the concrete

Mix (Specimen Number)	Substrate Concrete		Repair Concrete		Slump	
	Compressive (N/mm^2)	Average (N/mm^2)	Compressive (N/mm^2)	Average (N/mm^2)	Substrate Concrete (mm)	Overlay Concrete (mm)
01:06	362	376	348	354	135	140
07:12	390		368		125	135
13:18	264	258	371		135	140
19:24	252		356		122	125
25:30	150	150.5	361		120	120
31:36	151		320		120	110

5. 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 Ⅴ

Table Ⅴ Bonding materials and its technical Specifications

	Epoxy Adhesive		Latex Adhesive		Polypropylene Fiber
	Type Ⅰ	Type Ⅰ	Type Ⅰ	Type Ⅰ	
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/cm3
Accordance Specification	ASTM C 881	ASTM C 882	ASTM C 882	ASTM C 631	-----
Compressive Strengths (N/mm^2)	50-60	-------	35	-------	--------

6. Test Program and Specimens Preparation:

6.1.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 $\mathbf{f_{cu}}$=350, $\mathbf{f_{cu}}$=250 and $\mathbf{f_{cu}}$=150 kg/cm^2, however the repair concrete was high strength concrete with $\mathbf{f_{cu}}$=350 kg/cm^2, 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. Figure 1 shows the preparing of the test specimens

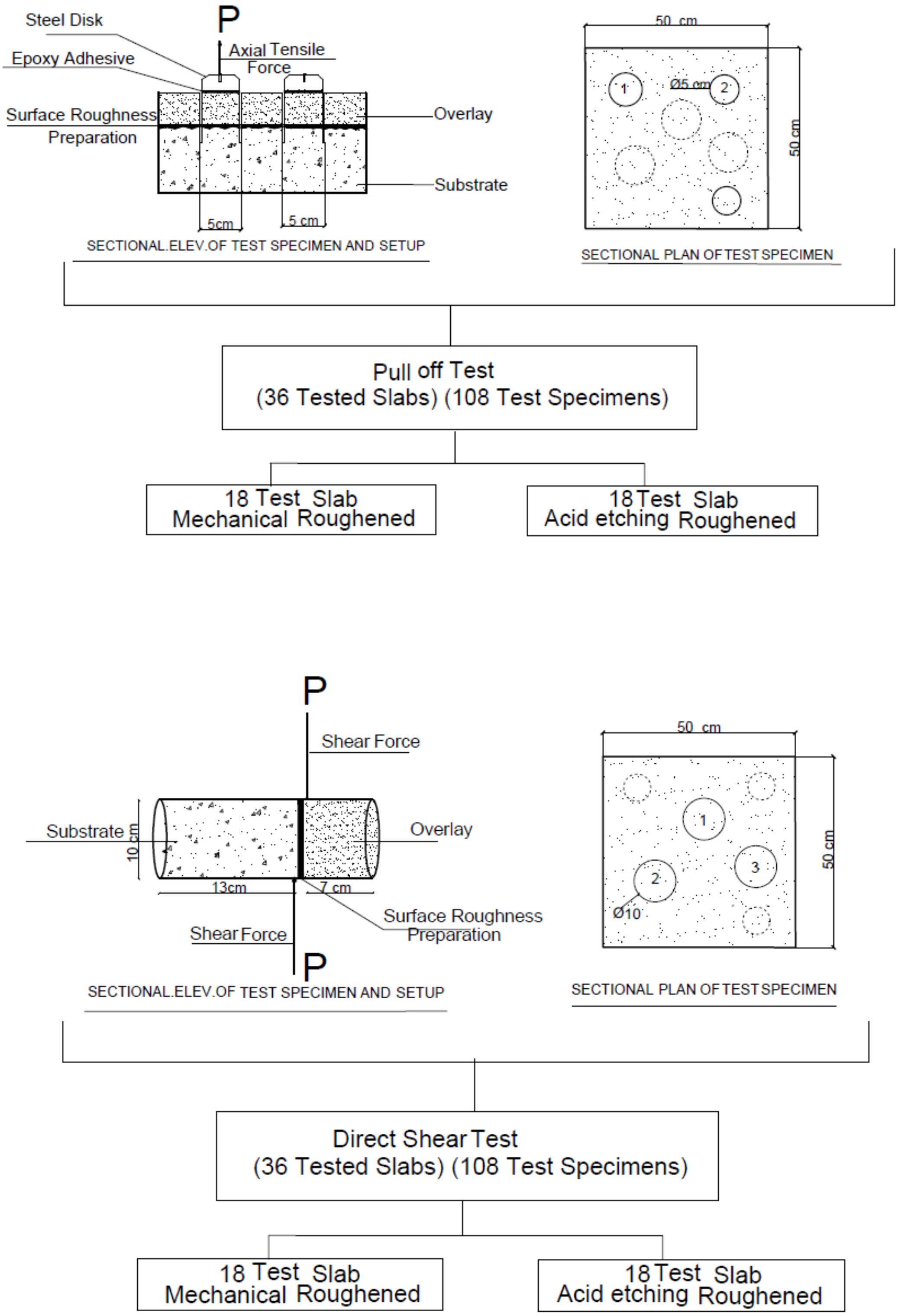

Figure 1: Diagrammatic sketch for the experimental program

Dimension of 500 mm * 500 mm * 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.

6.2.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 facce 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

Figure (3) Roughness Surface preparation for substrate concrete

7. 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).

A. 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.

Interface failure	Substrate failure	Overlay failure

Figure (4) Specimens after failure

B. 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:

$$f_t = \frac{P}{\frac{\pi}{4}d^2} \quad (\frac{N}{mm^2}) \qquad (1)$$

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.

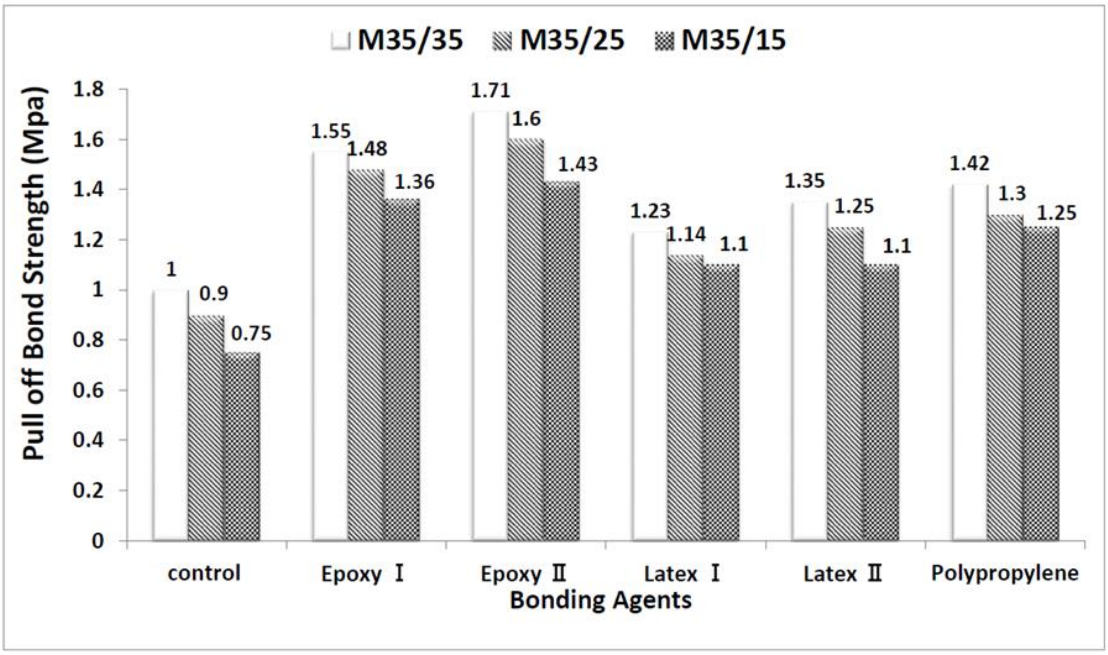

Figure (5): The mean pull-off bond strength for different bonding agents, Acid etching roughness, and quality concrete of substrate

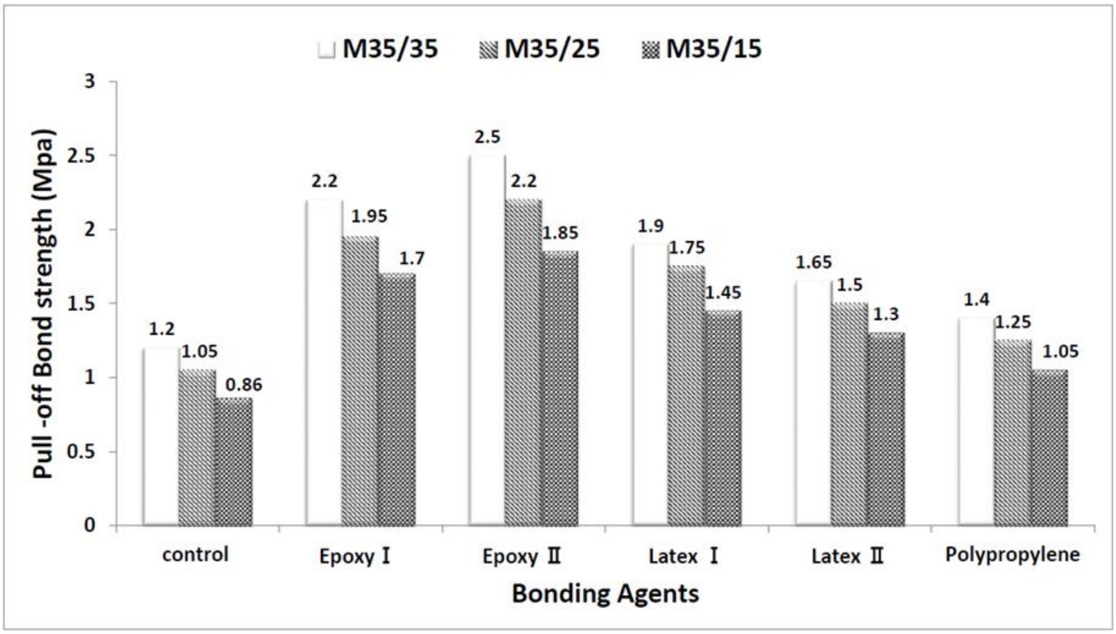

Figure (6): The mean pull-off bond strength for different bonding agents, mechanical roughness, and quality concrete of substrate

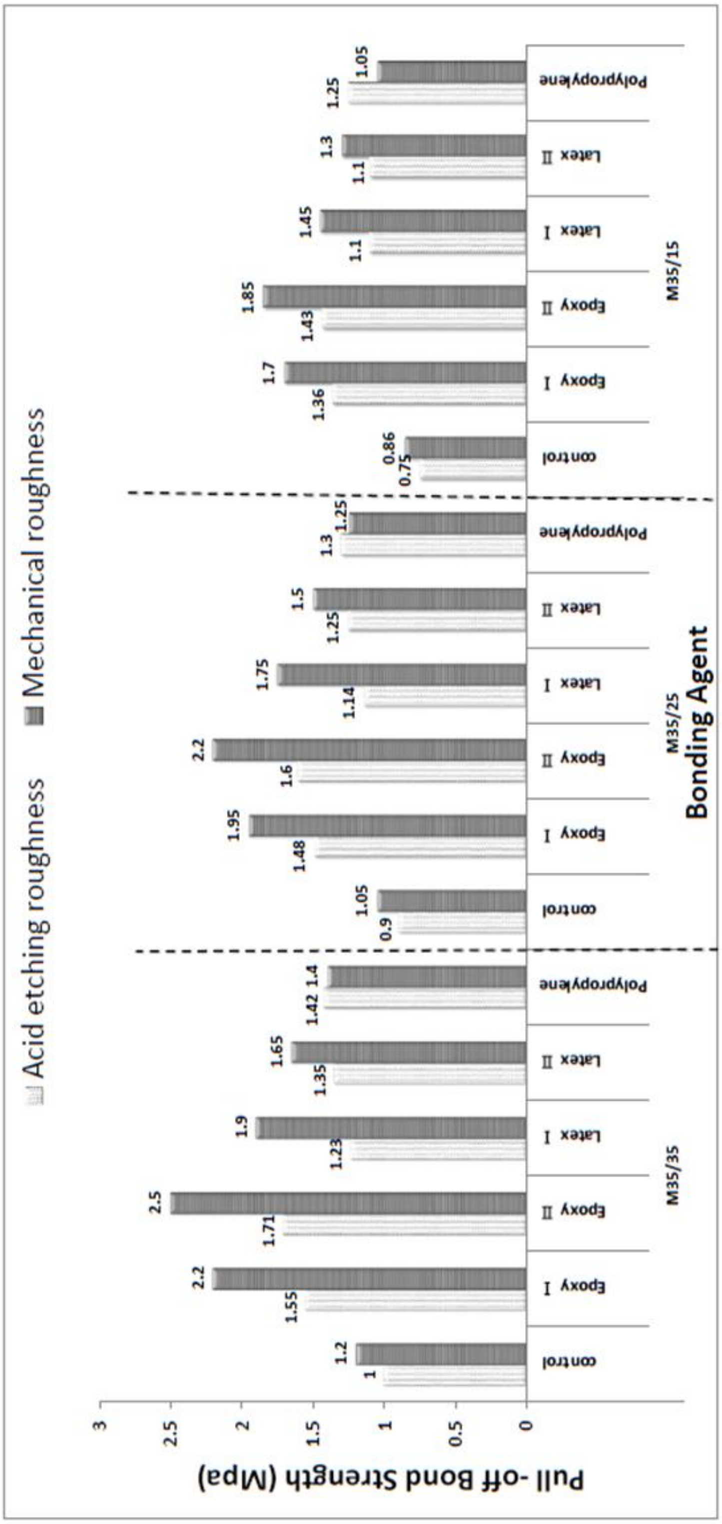

Figure (7): The mean pull-off bond strength vs. the surface

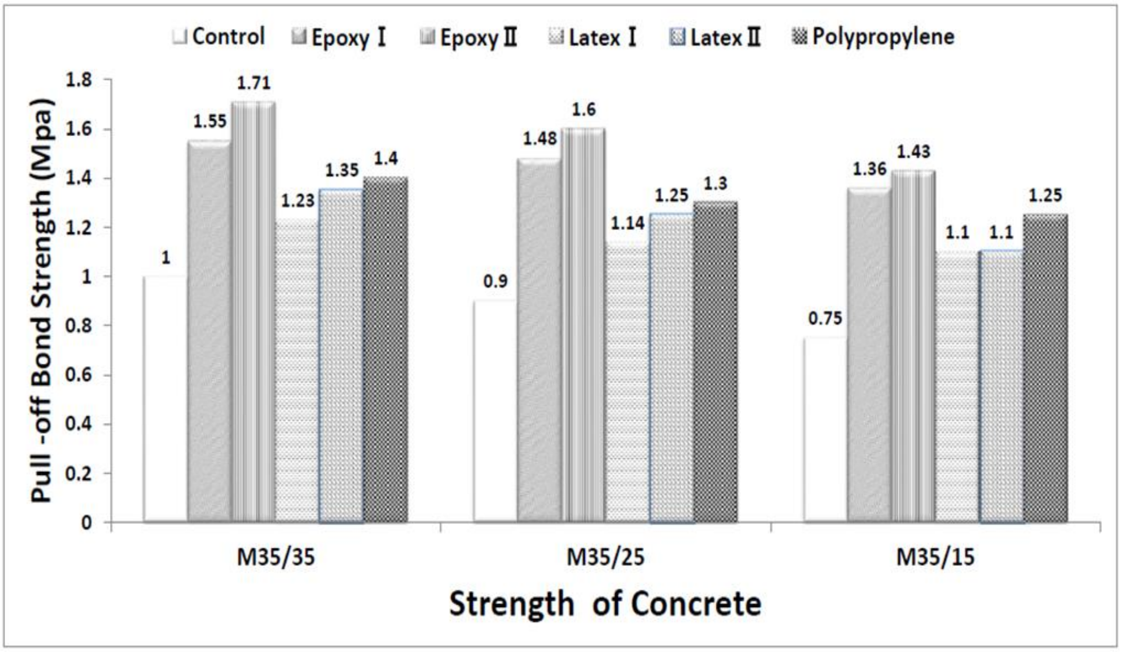

Figure (8): The mean pull-off bond strength for different quality concrete, different adhesive materials and acid etching roughness

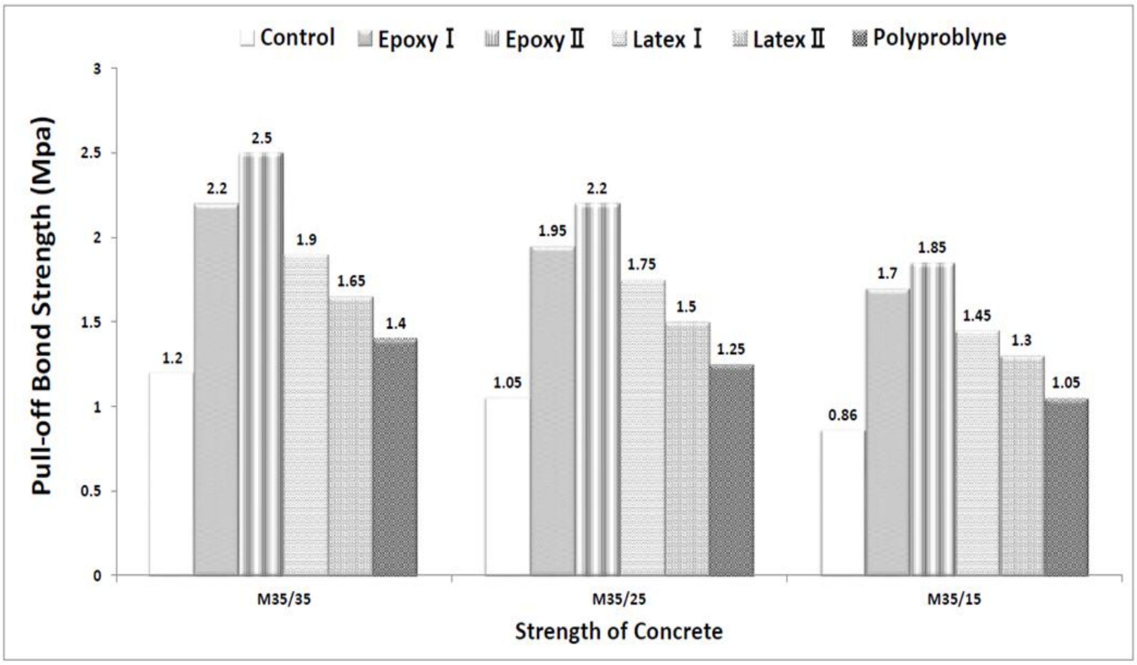

Figure (9): The mean pull-off bond strength for different quality concrete, different adhesive materials and mechanical roughness.

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.

C. 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).

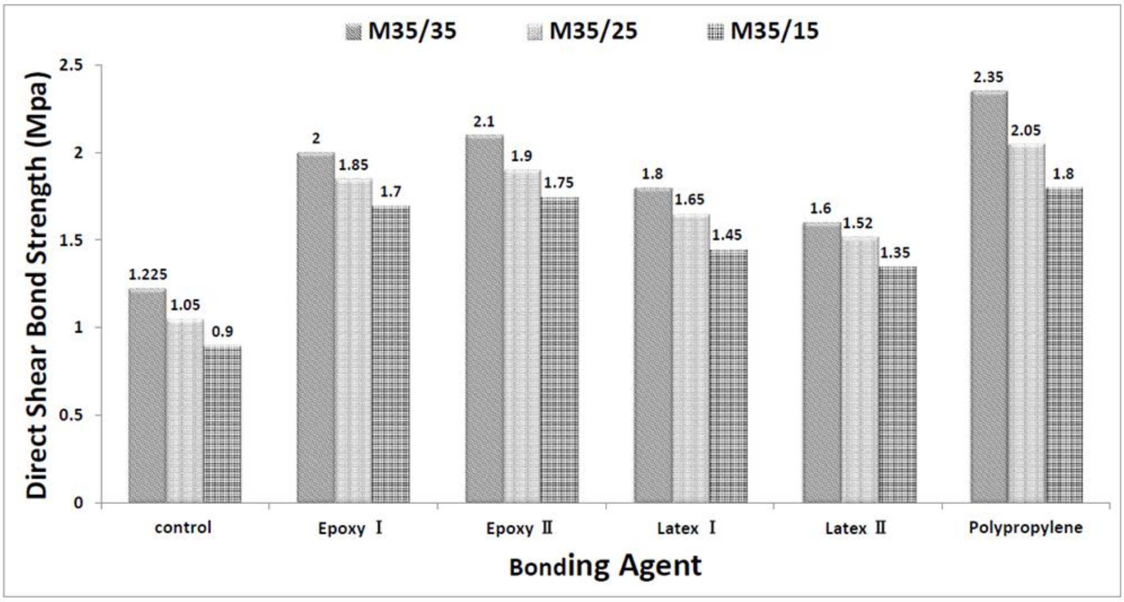

Figure (10): The mean direct shear bond strength for different bonding agents, Acid etching roughness, and quality concrete of substrate

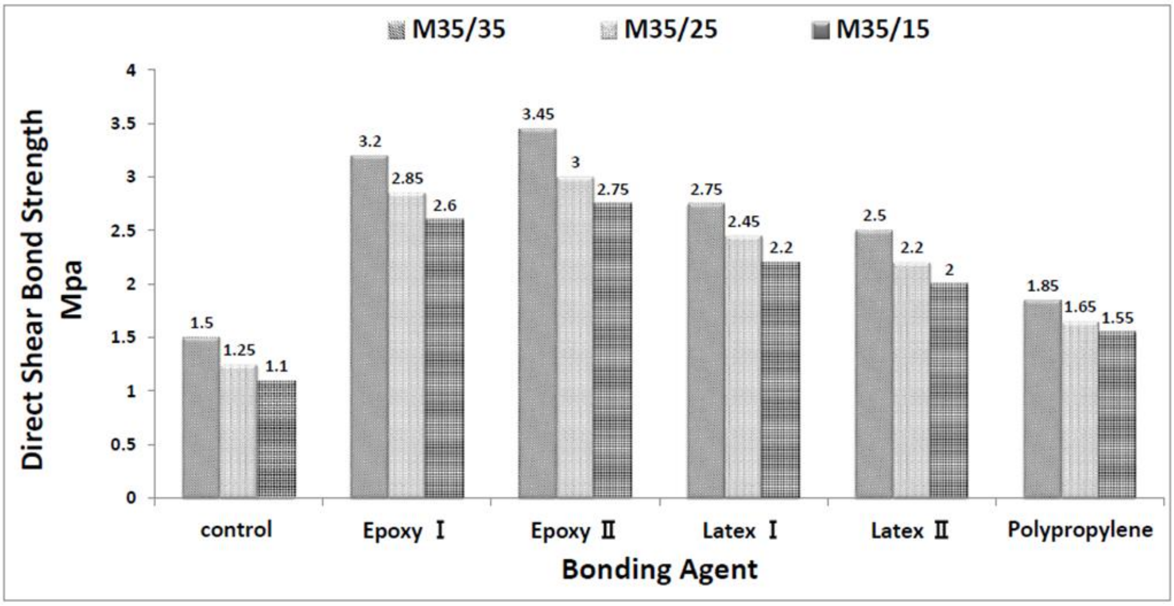

Figure (11): The mean direct shear bond strength for different bonding agents, mechanical roughness, and quality concrete of substrate

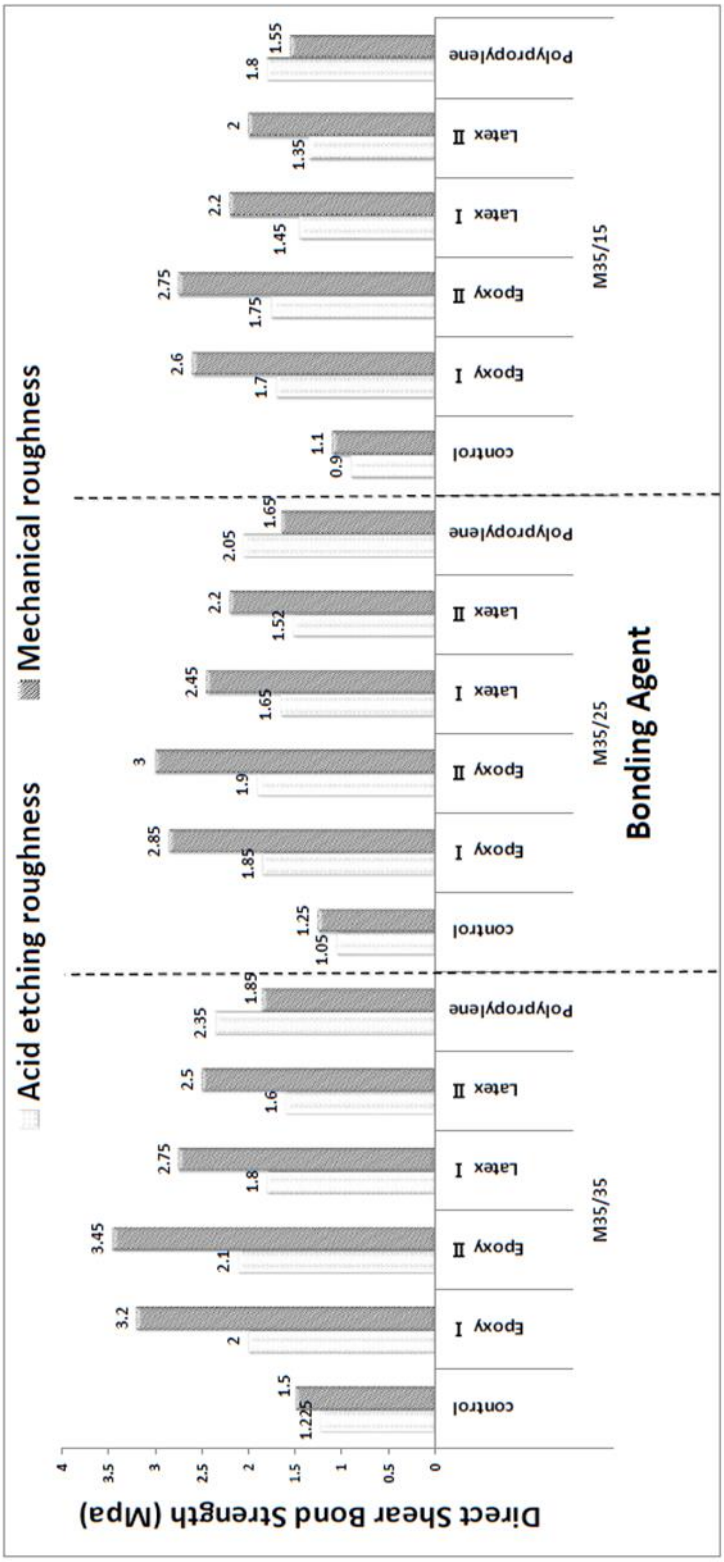

Figure (12): The mean Direct Shear bond strength vs. the surface

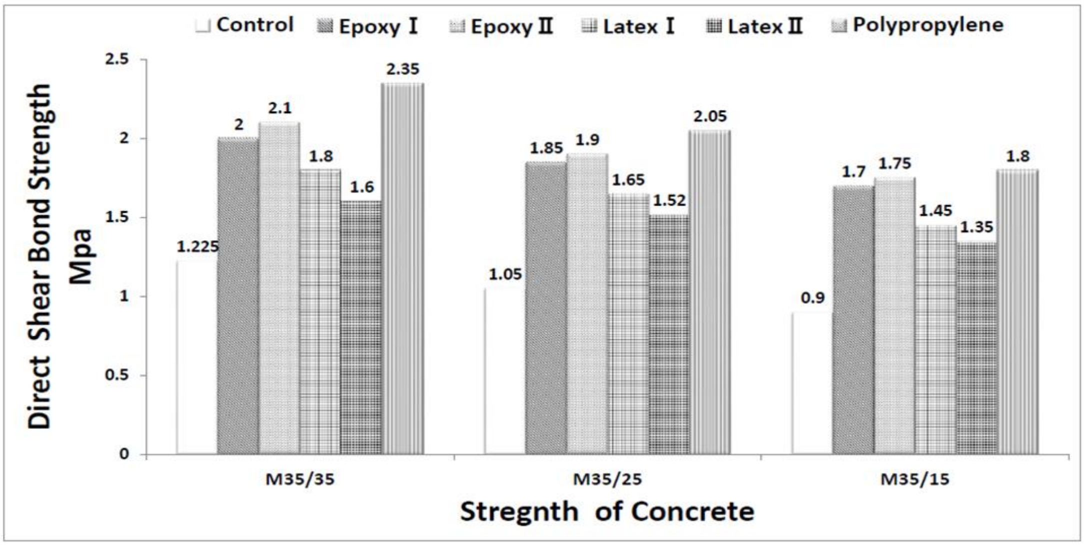

Figure (13): The mean Direct Shear bond strength for different quality concrete, different adhesive materials and acid etching roughness.

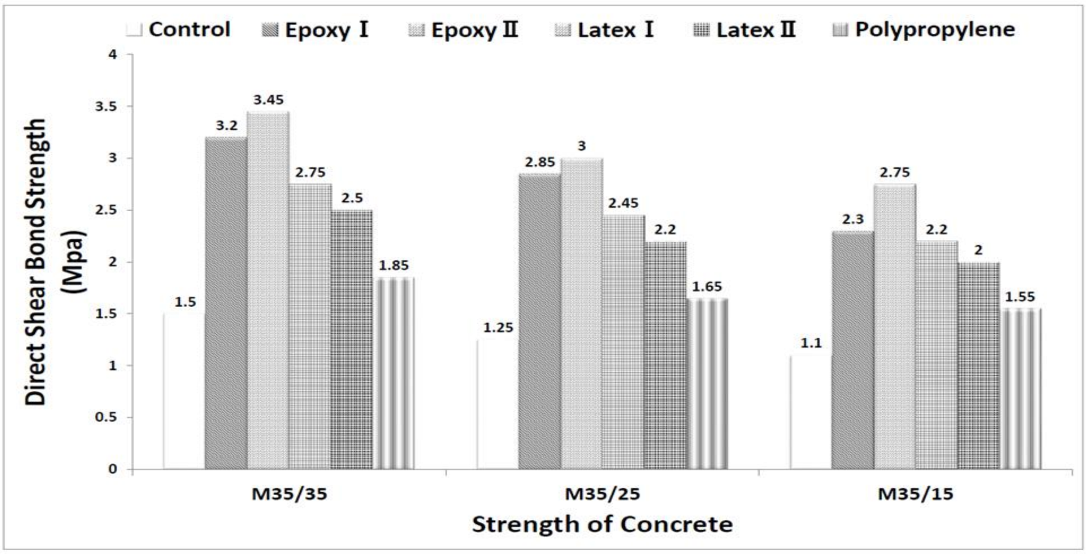

Figure (14): The mean direct shear bond strength for different quality concrete, different adhesive materials and mechanical roughness

D. Correlation between Shear Bond Strength and Tension Bond Strength:

Figures (15-16) show 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 by acid etching and mechanical methods without using bonding coat Figure (15) show linear relationships between the pull-off and direct shear bond strength without bonding agent with coefficients of correlation (R^2) equal 0.6468.

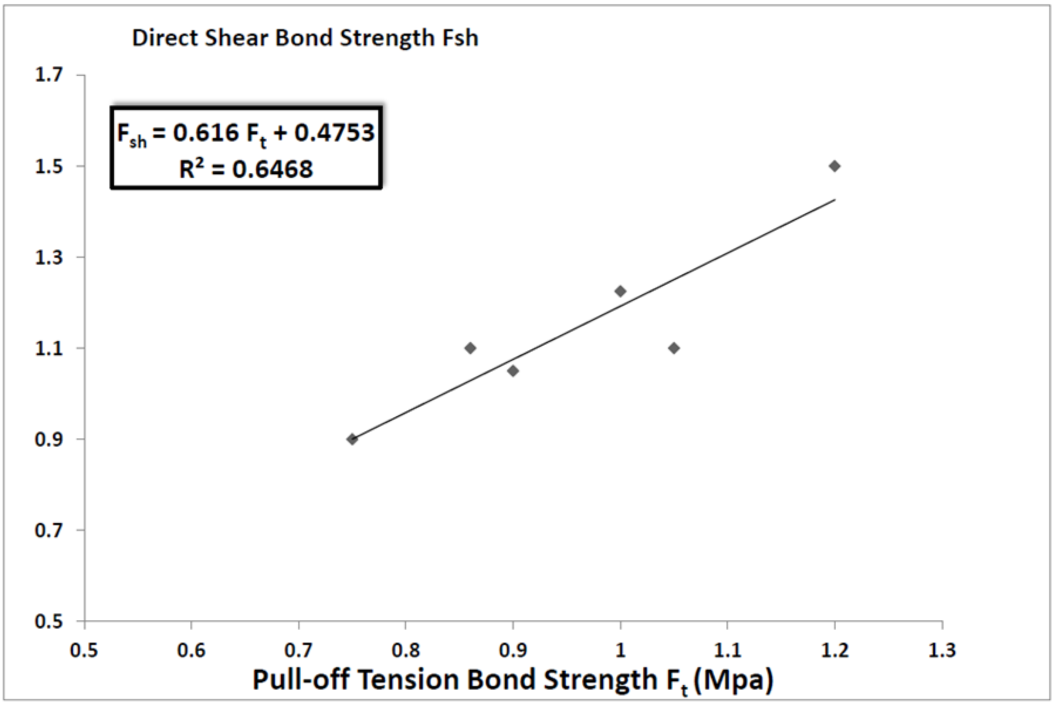

Figure (15): The correlation between Direct Shear Bond Strength and Pull-off Tensile Bond Strength. Without Bonding Agent

Figure (16) show linear relationships between the pull-off and direct shear bond strength with bonding agent with coefficients of correlation (R^2) equal 0.8854 and figure show are strongly correlated.

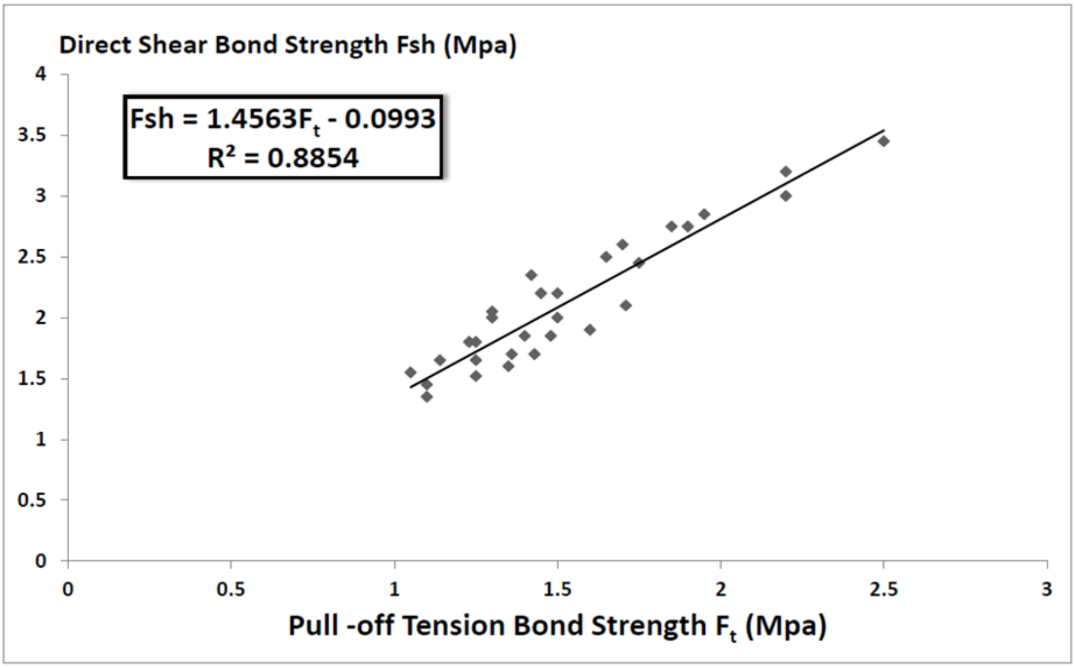

Figure (16): The correlation between Direct Shear Bond Strength and Pull-off Tensile Bond Strength. With Bonding Agent

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.

8. Conclusions

1. The repair concrete must be carefully selected of suitable repair systems. Choose of compatible repair concrete to substrate, and suitable type of agent to the roughness surface.

2. The bond strength of substrate concrete to new concrete increased significantly with the mechanical roughness or acid etching roughness.

3. Use of bonding coats significantly improved the bond strength. Bond strength increased by about 80% more than the corresponding non-adhesive control specimens for tensile bond strength and 150% for shear bond strength.

4. The addition of polypropylene fibers to the overlay concrete improved the bond strength to the substrate concrete beside other physical and mechanical properties.

5. The direct shear bond strength is moderately correlated to pull-off tensile bond strength without bonding agent. Coefficient of correlation R2 equals 0.6468. The following linear regression relationships might be estimated.

$$\boldsymbol{F_{sh} = 0.616\, F_t + 0.4753}$$

Where:

F_{sh} : The Direct shear bond strength in Mpa

F_t : The pull-off tensile bond strength in Mpa

6. The direct shear bond strength is strongly correlated to pull-off tensile bond strength with bonding agent. Coefficient of correlation R2 equal 0.8854. The following linear regression relationships might be estimated :

$$\boldsymbol{F_{sh} = 1.4563\, F_t - 0.0913}$$

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