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Evaluation of Different Surface Treatment Techniques Used To Improve Bond Strength between Old and New Concrete

Ahmed Fathy[1], Hany Elshafie [2], Mona M. Abdel Wahab [2], Ibrahim Abdel Latif [3]

1,2,3 Demonstrator, Associate Professor and Assistant Professor,
Structural Engineering Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt

ملخص البحث

يحتوي البحث على تحليل نتائج اختبارات معملية لتقييم الطرق المختلفة لمعالجة السطح المستخدمة لتحسين قوى الترابط بين الخرسانة القديمة والحديثة. ويتضمن البرنامج العملى استخدام مواد ربط مختلفة متاحة محلياً فى السوق المصرى، وكذلك دراسة اختلاف خشونة السطح وحالة الرطوبة والفترات الزمنية بين لصق المواد الإيبوكسية وصب الخرسانة. وقد تضمنت الدراسة تجهيز 28 عينة خرسانية تم ربطها باستخدام مواد ربط مختلفة ما بين مواد ايبوكسية ولاتكس وبوليستر لبيان تأثيرها على قوى التماسك. وقد تم تخشين سطح العينات اما كليا أو جزئياً. وتم الحفاظ على حالة السطح اما فى الحالة الجافة أو المشبعة. وقد أظهرت نتائج الدراسة فاعلية تجهيز السطح الخرسانى بالطرق المستمر خاصة عند الربط بمواد إيبوكسية وبالاخص عند التطبيق على سطح جاف للخرسانة المتصلدة.

ABSTRACT

This paper presents the results of an experimental study conducted to evaluate the different surface treatment techniques used to improve the bond strength between old and new concrete. The experimental work was designed to apply different bonding agents of different sources in the Egyptian market, surface roughness, moisture condition, and overlay time. The bonding coats used differs in chemical base, setting time, and viscosity. Researchers deals with the surface preparation as the most important factor affecting the bonding strength enhancement. In this study, twenty eight concrete specimens were bonded using latex modified cement slurry, epoxy resin and polyester from different commercially sources. Eleven specimens were partially roughened by chipping and other 17 specimens were fully roughened by hammering. Specimens' interfaces were kept in either air dry or saturated surface dry (SSD) moisture condition. The overlay time ranged from immediate overlay placing to 8 hours interval between applying epoxy and placing overlay concrete. The experimental results showed that higher bond strength results were obtained for epoxy bonded specimens especially on dry and fully roughened surfaces. Keeping substrates in saturated surface dry (SSD) condition enhances the bond strength of latex bonded specimens. Applying full roughness surface preparation does not enhance the bond strength of latex bonded specimens.

Keywords: Bond strength, Pull-off test, Epoxy, Latex, Roughness, Surface preparation, Moisture, Contact Time, Adhesives, Bonding coats.

1. Introduction

Concrete-to-concrete interfaces are mutually existed in new constructions as well as in rehabilitation and strengthening of existing structures. Undoubtedly repair and strengthening of concrete structures possess a vital role in extending their service life. Variant techniques like repair by concrete replacement and strengthening by jacketing require adding fresh concrete to hardened one. Casting concrete in large thickness elements like rafts also requires the same issue. Insufficient bond strength between different aged concrete layers will prevent the gross section to act monolithically resulting in a reduction in its performance allowing the debonding failure mode to occur at the interface.

The repair system can be considered as a three-phase composite system; overlay and bond zone. The bond strength mainly depends on adhesion in interface, friction, aggregate interlock, and time-dependent factors. Adhesion to interface depends on bonding agent, material compaction, cleanness and moisture content of repair surface, specimen age, and roughness of interface surface. Prior to the application of the overlay, the substrate surface is removed of any distressed concrete and prepared to ensure that a strong bond is formed between the two different concretes (Indrajit et al., 2005). Both the shorter setting time of bonding coat and the longer one required for pouring the repair layer form a great obstacle in the field.

Julio et al. (2005), Santos and Dias-da-Costa (2012) investigated the effect of using epoxy adhesives on the bond strength using slant shear test and pull-off test. Bonaldo et al. (2005) nominated different epoxy types to bond fresh steel fiber reinforced concrete (SFRP) overlay to concrete substrate using pull-off test. They concluded higher results for epoxy adhesives.

Preparation techniques, such as wire-brushing, sand-blasting, shot blasting, chipping and hydro-demolition, are frequently used to remove the superficial layer. Beushausen (2005), Bissonnette et al. (2008), Perez et al. (2009), Silfwerbrand et al. (2011), Talbot et al. (1994), Carter et al. (2002) and Julio, (2004) applied variant surface roughness techniques to prepare the interface. They concluded relatively higher results for sand blasting and water jetting. They got a correlation between bond results there.

Zhu (1992), Silfwerbrand (2003), Lukovic et al. (2012) and Martinola et al. (2001) changed the moisture condition of interface to analyze its effect on the bond strength. They concluded an adverse relation between moisture degree and bond strength for epoxy bonded concrete layers.

Nowadays some companies start to commercially produce epoxy adhesives in different viscosity and setting time. However, little attention has been given to analyze the effect of viscosity and overlay time on bond strength. Therefore, the aim of this study was to investigate the different surface roughness techniques, focusing on how to improve the bond strength between fresh and hardened concrete layers. This paper presents the experimental results of a representative evaluation of bond strength for variant locally available bonding materials, surface roughness, moisture condition, and contact time.

2. Experimental Work

There are five factors taken into consideration in the experimental study; 1) bonding agent type and source, 2) surface roughness, 3) moisture conditions of substrate surface and 4) open time.

Two surface roughness techniques were used in the experimental study, namely partial roughness and full roughness. Air dry and saturated surface dry (SSD) were used as substrates' surface conditions to investigate the effect of moisture condition on the bond strength. The overlay time was changed according to the used bonding agent data sheet specifications. Each of the mentioned variables was investigated to study its influence on the bond strength between different aged concrete layers.

2.1. Material Characterization

The cement used was Portland cement (CEM I 42.5 N) that complies with the requirement of the Egyptian standard specifications ES: 4756-1. The coarse aggregate was crushed stone. The used sand was natural sand. Two concrete mixes were used for concrete substrate and overlay to neutralize the effect of the concrete compressive strength on the bond strength between the different aged concrete layers. The concrete mix for concrete substrate was designed to achieve cube compressive strength after 28 days of 25 MPa and the concrete mix for concrete overlay was designed to achieve cube compressive strength after 28 days of 30 MPa. Table (1) shows the mix proportions and the properties of concrete layers in fresh and hardened conditions.

Table (1): Mix proportions and proprieties of concrete layers

Concrete Layers			Substrate Concrete	Overlay Concrete
Concrete Mix Proportions per $1m^3$	Cement	(Kg)	350	420
	Crushed Stone (S1)	(Kg)	590	896
	Crushed Stone (S2)	(Kg)	590	----
	Sand	(Kg)	640	794
	Water	(Liter)	222	250
Fresh Properities	Slump	(cm)	8.0	11.0
Hardened Properities	Compressive Strength	(MPa)	305	325
	Tensile Strength	(MPa)	2.6	3.2

2.2. Bonding Materials

Bonding materials used vary in chemical base, setting time, and viscosity. Five bonding agents were used; normal set epoxy of normal viscosity by source I (NS-NV EPOXY I), source III (NS-NV EPOXY III), long set epoxy of high viscosity by source II (LS-HV EPOXY II), long set epoxy of low viscosity by source II (LS-LV EPOXY II), polyester (P) by source IV, modified cement latex slurry by source I (LATEX I) and source II (LATEX II).

2.3. Details of Test Specimens

Twenty eight test specimens were used in the experimental program labelled according to Table (2). Sixteen test specimens' interfaces were fully roughened and the other ten were partially roughened before applying the different bonding agents. Two test specimens were prepared and tested without any bonding agent at the interface as a control test specimen for each roughness technique. The details of the tested specimens are listed in Table (3).

Table (2): Designation of test specimens

Specimen Code	Test Specimens
$B_{F\text{-}D}\ P_{LSHV\text{-}II\text{-}0}$	Full roughened (F) and air dry (D) substrate concrete (B) bonded with long set epoxy of high viscosity (LSHV) by source II and applied at contact time (0.0 hr.)
$B_{P\text{-}SSD}\ P_{NS\text{-}I\text{-}1}$	Partial roughened (P) and saturated surface dry (SSD) substrate concrete (B) bonded with normal set epoxy (NS) by source I and applied at contact time (1.0 hr.)

Table (3): Details of test specimens

Spec.	Code	Bonding Agent		Interface		Overlay Timing (hour)
		Type	Source	Roughness	Moisture Condition	
1	$B_{F\text{-}D}\,P_{LSHV\text{-}II\text{-}0}$	Long Set Epoxy of High Viscosity (LS-HV)	II	Full	Air Dry	0.00
2	$B_{F\text{-}D}\,P_{LSHV\text{-}II\text{-}1}$			Full	Air Dry	1.00
3	$B_{F\text{-}D}\,P_{LSHV\text{-}II\text{-}4}$			Full	Air Dry	4.00
4	$B_{F\text{-}D}\,P_{LSHV\text{-}II\text{-}8}$			Full	Air Dry	8.00
5	$B_{P\text{-}D}\,P_{LSHV\text{-}II\text{-}0}$			Partial	Air Dry	0.00
6	$B_{F\text{-}D}\,P_{LSLV\text{-}II\text{-}0}$	Long Set Epoxy of Low Viscosity (LS-LV)	II	Full	Air Dry	0.00
7	$B_{F\text{-}D}\,P_{LSHV\text{-}II\text{-}1}$			Full	Air Dry	1.00
8	$B_{F\text{-}D}\,P_{LSHV\text{-}II\text{-}2}$			Full	Air Dry	2.00
9	$B_{F\text{-}D}\,P_{LSHV\text{-}II\text{-}3}$			Full	Air Dry	3.00
10	$B_{P\text{-}D}\,P_{LSHV\text{-}II\text{-}0}$			Partial	Air Dry	0.00
11	$B_{F\text{-}D}\,P_{NS\text{-}I\text{-}0}$	Normal Set Epoxy of Normal Viscosity (NS-NV)	I	Full	Air Dry	0.00
12	$B_{F\text{-}D}\,P_{NS\text{-}I\text{-}0.5}$			Full	Air Dry	0.50
13	$B_{F\text{-}D}\,P_{NS\text{-}I\text{-}1}$			Full	Air Dry	1.00
14	$B_{F\text{-}SSD}\,P_{NS\text{-}I\text{-}0}$			Full	SSD	0.00
15	$B_{P\text{-}D}\,P_{NS\text{-}I\text{-}0}$		I	Partial	Air Dry	0.00
16	$B_{P\text{-}SSD}\,P_{NS\text{-}I\text{-}0}$		I	Partial	SSD	0.00
17	$B_{P\text{-}D}\,P_{NS\text{-}III\text{-}0}$		III	Partial	Air Dry	0.00
18	$B_{P\text{-}SSD}\,P_{NS\text{-}0}$		III	Partial	SSD	0.00
19	$B_{F\text{-}D}\,P_{P\text{-}IV\text{-}0}$	Polyester (P)	IV	Full	Air Dry	0.00
20	$B_{F\text{-}SSD}\,P_{P\text{-}IV\text{-}0}$		IV	Full	SSD	0.00
21	$B_{P\text{-}D}\,P_{P\text{-}IV\text{-}0}$		IV	Partial	Air Dry	0.00
22	$B_{J\text{-}D}\,P_{LAT\text{-}II\text{-}0}$	Modified Cement Latex Slurry (LATEX)	II	Full	Air Dry	0.00
23	$B_{J\text{-}SSD}\,P_{LAT\text{-}II\text{-}0}$		II	Full	SSD	0.00
24	$B_{2\text{-}D}\,P_{LAT\text{-}II\text{-}0}$		II	Partial	Air Dry	0.00
25	$B_{2\text{-}D}\,P_{LAT\text{-}I\text{-}0}$		I	Partial	Air Dry	0.00
26	$B_{2\text{-}SSD}\,P_{LAT\text{-}I\text{-}0}$		I	Partial	SSD	0.00
27	$B_{J\text{-}SSD}\,P_{CTR\text{-}0}$	Non-adhesive (CONTROL)	---	Full	SSD	0.00
28	$B_{P\text{-}SSD}\,P_{CTR\text{-}0}$		---	Partial	SSD	0.00

2.4. Preparation of Test Specimens

2.4.1. Specimens Configuration

Figure (1) shows that the test specimens have dimensions 30×30×15 cm; the lower 10 cm for the substrate, and the upper 5 cm for the overlay concrete layer. Each test specimen was then prepared to be tested in 3 different places.

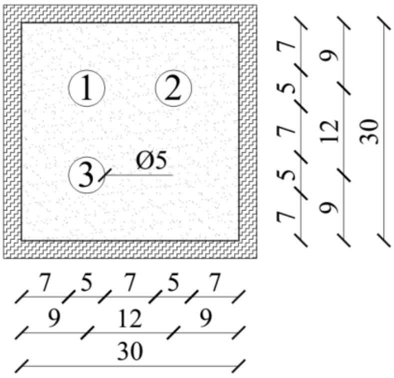

Figure (1): Plan of test specimen configuration

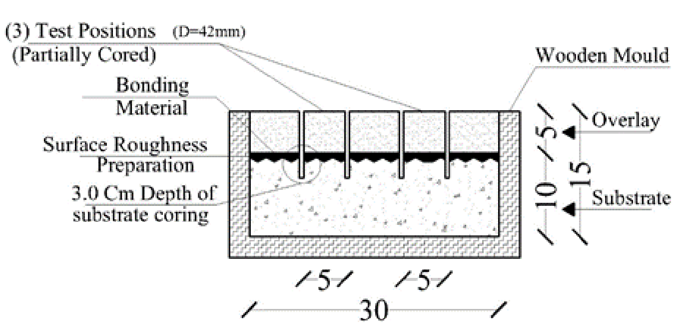

Figure (2): Sectional elevation of test specimen

2.4.2. Surface Preparation

Two techniques had been used to roughen the interface namely partial roughness by chipping and full roughness by hammering. The used mechanical methods are the most common techniques in sites, representing the locally available roughness techniques that did not need a great expertise for labors.

Eighteen test specimens were fully roughened. A light weight hammer of 3 kg was used to remove the weak laitance concrete layer formed by bleeding. Hammering has been continued reaching the coarse aggregates' surface within a depth of 5.0 mm as presented in Figure (3).

Figure (3): Interface surface profile of hammered test specimen

Ten test specimens were partially roughened. A hand held driller was applied on a fair face concrete interface. A grid of 3.0 cm spacing was plotted where the driller was applied within 1 cm inside the interface as presented in Figure (4).

(a) Partial chipping grid at interface | (b) Interface surface profile of partially roughened test specimen | (c) Interface surface profile of partially roughened test specimen

Figure (4): Partial chipping of test specimens

2.4.3. Moisture Condition

Two different moisture conditions were applied observing their influence on bond strength. Substrates were considered as in air dry condition when they had been left in the ambient room condition for 24 hours at 24^{o} C. Other substrates were also considered as in SSD condition when they had been kept damp for sometimes and before applying any adhesive by 2 hours. Adjusting the moisture condition either in air dry or in SSD states after completing the 7 days curing of the overlay concrete.

2.5. Application of Bonding Materials

In the current research adhesives components were mechanically mixed according to the produced data sheet. Then they were applied on a clear interface free from grease, dust, and deposits. At the age of 28 days of concrete substrate; adhesives were applied within their specified thickness in two orthogonal directions. Epoxy adhesives were applied also within their pot life time duration after mixing its components. Resins and hardeners were mixed by the specified mixing ratio from the producer. Adhesives were applied at summer season of about 35^{o} C.

Adhesives had been checked to be still tacky before overlay concrete was casted till the molds edge (5.00 cm thickness), and compacted by the tamping rod. Overlay concrete layers were placed as a fresh concrete layer on hardened concrete substrate of 28 days age. Overlay concrete was compacted by applying the tamping rod for 25 times. Finishing was carried out by the trowel as presented in Figures (5 and 6).

Figure (5): Placing of overlay concrete

Figure (6): Finishing of overlay concrete

2.6. Test Setup

Figure (7) shows the test setup used in this study. A core drill was used for preparing the test specimens with a core barrel of 50 mm nominally outside diameter and 42 mm inside diameter. Test Specimens were drilled at the age of 28 days for concrete overlay and 56 days for concrete substrate. The test specimens were fixed thoroughly and the core drill was also fixed to eliminate vibrations occurred during coring. The core barrel was allowed to cut the test specimens to a depth of 8 cm from it surface (i.e. 5 cm overlay thickness and 3 cm inside the substrate). Verticality was ensured during drilling to avoid any slope or eccentricity of load application.

A steel disk of 50 mm diameter, and 25 mm thickness was attached to the drilled part of the test specimen with epoxy adhesive. Epoxy adhesive was prevented from leakage inside the circular cut of the concrete. The steel disk has a threaded hole of about 10 mm diameter to be well attached to the testing device. The three legs of the pull-off tester were well adjusted to ensure the horizontality of the device plate, so a bubble balancer was used as presented in Figure (8).

A pull-off apparatus was used for loading. The tensile load was applied gradually through the device's crank. A 50 KPa/s was applied according to ASTM C1583 04. It was adjusted through the crank, and monitored through the digital manometer. Loading continued till failure of bond between overlay and substrate concrete.

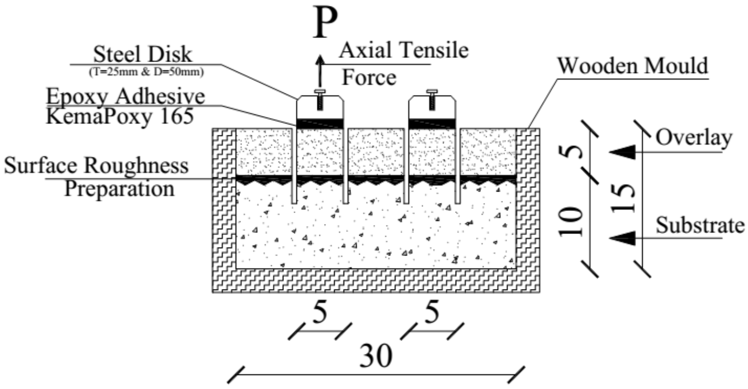

Figure (7): The test setup

Figure (8): Water bubble levelling of the device base

3. Pull-off Test Results

The results of the failure stress and its corresponding failure mode of the Pull-off test were summarized in Tables (4 and 5).

Table (4): Pull-off test results

Spec.	Code	Bonding Agent		Interface		Overlay Timing (hour)	Failure Mode	Mean Strength (MPa)	C.O.V (%)
		Type	Source	Roughness	Moisture Condition				
1	$B_{F-D}\,P_{LSHV-II-0}$	Long Set Epoxy of High Viscosity (LS-HV)	II	Full	Air Dry	0.00	Interface	2.50	26.73
2	$B_{F-D}\,P_{LSHV-II-1}$			Full	Air Dry	1.00	Interface	1.88	2.13
3	$B_{F-D}\,P_{LSHV-II-4}$			Full	Air Dry	4.00	Interface	1.20	2.09
4	$B_{F-D}\,P_{LSHV-II-8}$			Full	Air Dry	8.00	Interface	0.97	2.59
5	$B_{P-D}\,P_{LSHV-II-0}$			Partial	Air Dry	0.00	Interface	1.41	1.00
6	$B_{F-D}\,P_{LSLV-II-0}$	Long Set Epoxy of Low Viscosity (LS-LV)	II	Full	Air Dry	0.00	Interface	2.35	6.04
7	$B_{F-D}\,P_{LSHV-II-1}$			Full	Air Dry	1.00	Interface	2.00	17.46
8	$B_{F-D}\,P_{LSHV-II-2}$			Full	Air Dry	2.00	Interface	1.82	19.38
9	$B_{F-D}\,P_{LSHV-II-3}$			Full	Air Dry	3.00	Interface	0.92	8.40
10	$B_{P-D}\,P_{LSHV-II-0}$			Partial	Air Dry	0.00	Interface	1.46	2.74
11	$B_{F-D}\,P_{NS-I-0}$	Normal Set Epoxy of Normal Viscosity (NS-NV)	I	Full	Air Dry	0.00	Interface	1.44	1.08
12	$B_{F-D}\,P_{NS-I-0.5}$			Full	Air Dry	0.50	Interface	2.10	2.71
13	$B_{F-D}\,P_{NS-I-1}$			Full	Air Dry	1.00	Interface	1.60	8.53
14	$B_{F-SSD}\,P_{NS-I-0}$			Full	SSD	0.00	Interface	1.40	3.55
15	$B_{P-D}\,P_{NS-I-0}$		I	Partial	Air Dry	0.00	Interface	1.35	---
16	$B_{P-SSD}\,P_{NS-I-0}$		I	Partial	SSD	0.00	Interface	0.90	24.27
17	$B_{P-D}\,P_{NS-III-0}$		III	Partial	Air Dry	0.00	Interface	1.42	4.98
18	$B_{P-SSD}\,P_{NS-0}$		III	Partial	SSD	0.00	Interface	1.26	37.66
19	$B_{F-D}\,P_{P-IV-0}$	Polyester (P)	IV	Full	Air Dry	0.00	De-bonding	---	---
20	$B_{F-SSD}\,P_{P-IV-0}$		IV	Full	SSD	0.00			
21	$B_{P-D}\,P_{P-IV-0}$		IV	Partial	Air Dry	0.00			
22	$B_{F-D}\,P_{LAT-II-0}$	Modified Cement Latex Slurry (LATEX)	II	Full	Air Dry	0.00	Interface	1.05	1.60
23	$B_{F-SSD}\,P_{LAT-II-0}$		II	Full	SSD	0.00	Interface	1.76	---
24	$B_{P-D}\,P_{LAT-II-0}$		II	Partial	Air Dry	0.00	Interface	1.21	11.11
25	$B_{P-D}\,P_{LAT-I-0}$		I	Partial	Air Dry	0.00	Interface	1.36	3.68
26	$B_{P-SSD}\,P_{LAT-I-0}$		I	Partial	SSD	0.00	Interface	1.73	---
27	$B_{F-SSD}\,P_{CTR-0}$	Non-adhesive (CONTROL)	---	Full	SSD	0.00	Interface	1.09	6.65
28	$B_{P-SSD}\,P_{CTR-0}$		---	Partial	SSD	0.00	Interface	1.26	14.41

* Control test specimens bonded without any adhesive with fully roughened (F), or partially roughened interface (P).
* Mean pull-off strength was calculated from 3 points of testing for each test specimen.
* Great concern for interface failure modes; where the mean bond strength was calculated.
* Substrate and overlay failure modes were excluded for factorial comparison.

Table (5): Failure Modes

Code	Failure Shape	Details of the Failure Surface
Fully Roughened Test Specimens		
LS-HV		- Bond interface failure. - Significant % of the failure plane has a remaining pure adhesive. - Aggregate paste bond failure in some coarse aggregates inside the cross section at contact (0.0 hour), but after (1.0 hour); it turns to cement paste failure.
LS-LV		- Bond interface failure and sometimes become deeper to be substrate interface failure. - Combination of paste failure and aggregate paste bond failure in some coarse aggregates inside the failure plane.
NS-NV		- Bond interface failure. - Significant % of the failure plane has a remaining pure adhesive. - Combination of paste failure and aggregate paste bond failure in some coarse aggregates inside the failure plane.
Latex		- Variant modes of failure between bond substrate, interface, and overlay failure. - Sometimes a significant % of the failure plane has a remaining pure adhesive. - Combination of paste failure and aggregate paste bond failure in some coarse aggregates inside the failure plane.
Control		- Bond interface failure. - Combination of paste failure and aggregate paste bond failure in some coarse aggregates inside the failure plane.
Partially Roughened Test Specimens		
LS-HV		- Bond substrate-interface failure. - Combination of paste failure and aggregate paste bond failure in some coarse aggregates inside the failure plane which were exposed.
LS-LV		- Bond substrate-interface failure. - Combination of paste failure and aggregate paste bond failure in some coarse aggregates inside the failure plane which were exposed.
NS-NV		- Bond substrate-interface failure. - Combination of paste failure and aggregate paste bond failure in some coarse aggregates inside the failure plane which were exposed. - Some small voids were existed at the failure plane.
Latex		- The failure mode varies between bond interface and substrate interface failure. - Sometimes combination of paste failure and aggregate paste bond failure in some coarse aggregates inside the failure plane which were exposed, and in other times it become cement paste failure only. - Sometimes a significant % of the failure plane has a remaining pure adhesive.
Control		- Bond substrate-interface failure. - Combination of paste failure and aggregate paste bond failure in some coarse aggregates inside the failure plane which were exposed.

4. Discussion of Test Results

Table (4) presents the pull-off test results of the experimental study. The mean value of bond strength was calculated from 3 test records. The main scope of the current study is to investigate the bond strength under some variables. Therefore the bond strength records of substrate failure were excluded from calculations. It should be well noticed that all bond strength records were lower than the concrete tensile strength.

4.1. The Influence of Overlay Timing on Bond Strength of Epoxy Bonded Concrete Layers

The relationship between overlay timing and bond strength is illustrated in Figure (9) for epoxy bonded specimens. The figure presents the bond strength reduction with overlay timing. The ultimate bond strengths occurred at zero overlay timing, air dry substrate interface, and fully roughened surface; were 2.50 MPa, and 2.35 MPa for LS-HV and LS-LV in order. The bond strength of 1, 4, and 8 hours overlay timing of fully roughened interfaces were 75%, 48%, and 38% of the ultimate bond strength of LS-HV epoxy bonded specimens. The bond strength of 1, 2, and 3 hours overlay timing of fully roughened interfaces were 85%, 77%, and 39% of the ultimate bond strength of LS-LV epoxy bonded specimens.

For NS-NV, the ultimate bond strength occurred was 2.10 MPa at 0.50 hour overlay timing. The bond strength of 0 and 1 hour overlay timing of fully roughened air dry interfaces were 68%, and 76% of the ultimate bond strength occurred.

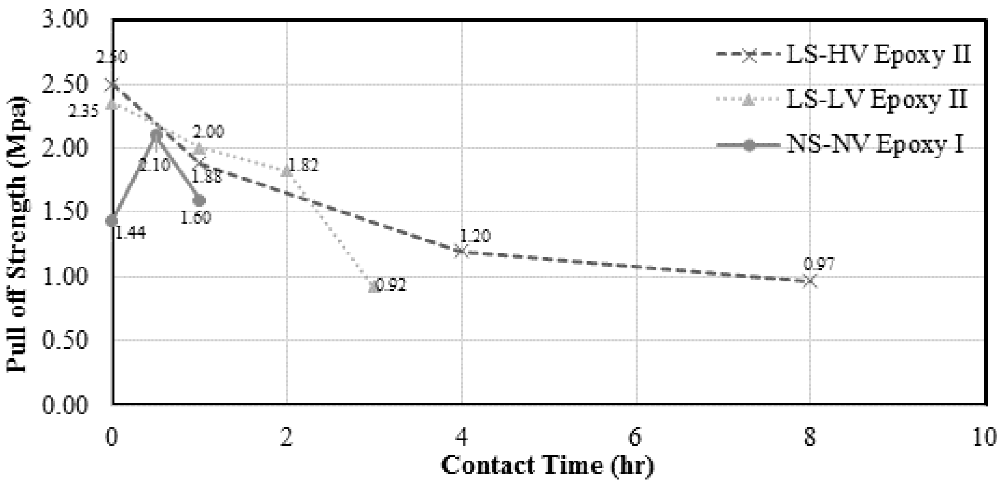

Figure (9): Pull off strength vs overlay timing

4.2. Influence of Substrate's Moisture Condition on Bond Strength

Figure (10) presents the relationship between moisture condition of substrate and bond strength. It was shown that the epoxy adhesives have higher bond strength at dry substrate moisture condition than in SSD one. At fully roughened and SSD interfaces; the NS-NV I epoxy bonded specimens produced 97% of its air dry bond strength. However, at partially roughened interfaces; the NS-NV I epoxy bonded specimens produced 67% of its dry bond strength. The effect of commercial source appeared when NS-NV III produced 89% of its dry bond strength. Therefore the reduction in bond strength for epoxy bonded test specimens in SSD substrate may be due to the effect of applying an epoxy adhesive on moist substrate concrete which probably affects the chemical reactions as previously mentioned.

The figure also presents that latex adhesives have higher bond strength at SSD substrate moisture condition than in dry conditions. At fully roughened interfaces and SSD substrates, latex II produced 167% of its dry bond strength, and 178% at partially roughened ones. The reduction in bond strength for the modified cement bonded specimens with a dry moisture condition may be due the absorption of the latex mixing water by the concrete dry substrate especially that was intentionally minimized.

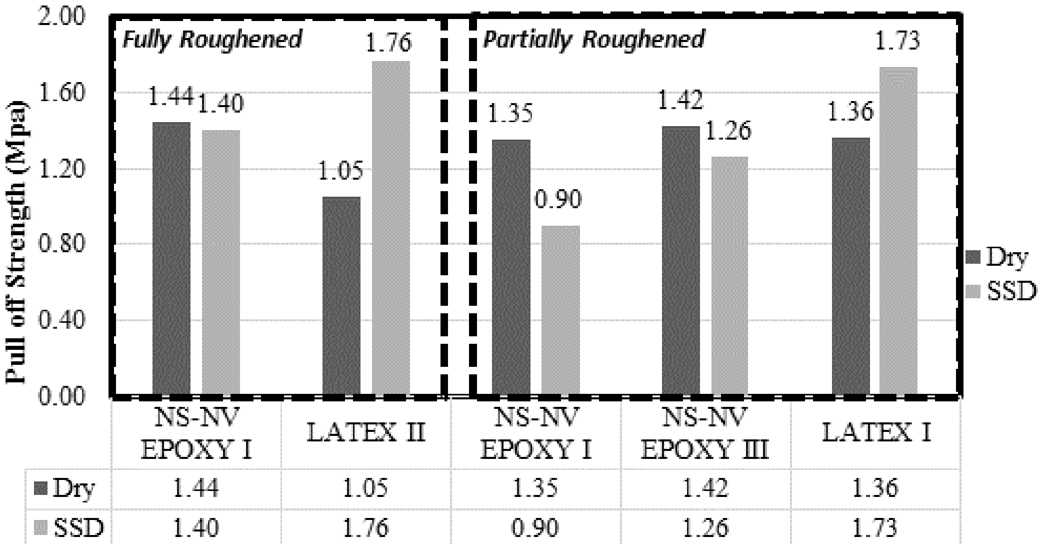

Figure (10): Pull off strength vs. moisture condition

4.3. Influence of Substrate's Surface Roughness on Bond Strength

Figure (11) presents the relationship between substrate surface roughness and bond strength. It was shown that higher bond strength was produced by epoxy bonded test specimens on fully roughened interfaces than partially ones. It was also found that higher bond strength was produced for latex bonded test specimens on partially roughened interfaces than roughened ones.

For LS-HV(II), LS-LV(II), NS-NV(I) epoxy bonded, partially roughened, and air dry test specimens produced 56%, 62%, and 70% respectively of those which were fully roughened. While for SSD condition, the NS-NV (I) epoxy bonded and partially roughened test specimens produced 64% of fully roughened ones. The higher bond strength gained by fully roughened specimens bonded by epoxy adhesives may be due to the full laitance removal, and the uniformity of the interface especially when focusing on the adhesive component of bond strength by applying the pull off test as a main evaluation and testing method. That matter changed when applying the latex bonding agent.

For the air dry state of moisture condition of substrate concrete bonded by latex (I) and (II); the partially roughened test specimens produced 110% and 115% respectively of those which were fully roughened. While for the SSD state of moisture condition of substrate concrete bonded by latex (I), the partially roughened test specimens produced 108% of bond strength in fully roughened ones. Partially roughened test specimens may have higher bond strength when they had been bonded by cement modified latex due to the higher interlocking effect by grooving.

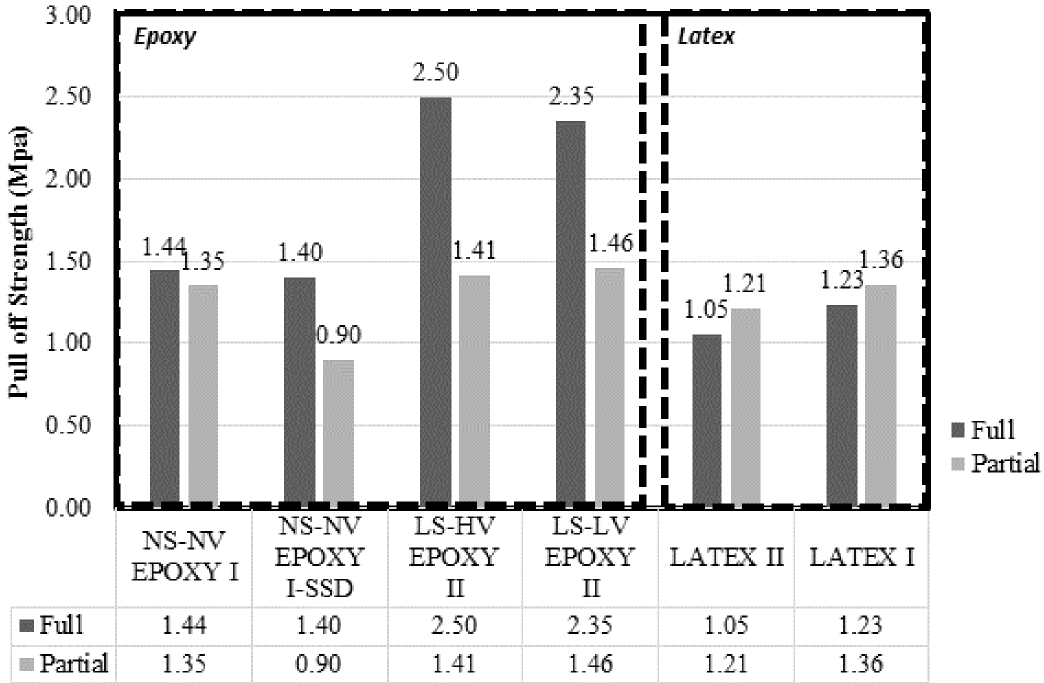

Figure (11): Pull off strength vs. surface roughness technique

4.4. Comparison between Different Types of Bonding Agents

Higher bond strength values were obtained by epoxy adhesives. The ultimate bond strength occurred at LS-HV epoxy by 2.50 MPa, while 94% and 84% of that ultimate strength were recorded by LS-LV and NS-NV epoxies respectively. The latex adhesives presented lower bond strength of 70% of the epoxy ultimate bond strength as presented in Figure (12). The presented figure based on a comparison between ultimate bond strength of different adhesives at variant conditions. They are common as being fully roughened interfaces. The NS-NV epoxy bond strength was recorded at 0.50 hour overlay timing and the latex one at SSD moisture condition.

The bond strength produced by all bonding agents fulfil the acceptance criteria of 1.70 MPa minimum required bond strength (ACI 548-11, 2012). The adhesive's efficiency can be presented as 67%, 100%, 124%, and 138% as bond increase percentage from the non-adhesive test specimens for Latex, NS-NV, LS-LV, and LS-HV in order.

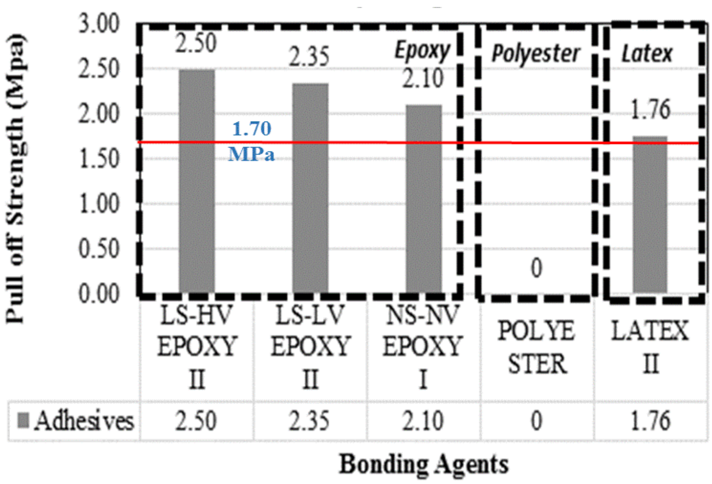

Figure (12): Pull off strength vs. bonding agents

5. Conclusions

Based on the experimental results carried out in this study, key research findings can be summarized as follows:

1. Epoxy bonded test specimens produce up to 42% higher bond strength than latex ones at fully roughened interfaces. However closer values were observed at partial roughening.
2. Full roughening of surfaces can raise the bond strength up to 77% for epoxy bonded surfaces related to those were partially roughened. While partial roughening could only enhance the latex applied ones by 15% related to those were fully roughened.
3. The surface roughness impact on the epoxy applied concrete bond strength increase % reaches 5 times that of latex ones.
4. Epoxy adhesives should be applied on an air dry surface where up to 55% increase in bond strength could occur at partially roughened surfaces.
5. Latex adhesives should be applied on an SSD surface where up to 67% increase in bond strength could occur.
6. The moisture impact on bond strength for epoxy adhesives is remarkable at partial roughening, on contrary in latex bonding agents.
7. Higher bond strength results could be obtained for long set epoxy adhesives at lower overlay timing.
8. The normal set epoxy should be applied at 30 minutes overlay time to obtain 46% higher bond strength.
9. Overlay timing should be considered while applying any epoxy to avoid bond breaker formation instead of bonding agent as 1.5, 3.0 and 5.5 hours for NS-NV, LS-LV and LS-HV in order.
10. Sometimes polyester adhesives in steel to concrete bonding or in hardened to hardened concrete bonding. The de-bonding failure occurred in the polyester bonded specimens before testing may be due to the effect of the mixing water existed in the fresh concrete layer. Water addition to polyester applied interface may stopped the chemical reaction between resin and hardener.

References

ASTM C1583, (2004), “Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method),” American Society for Testing and Materials.

Beushausen, H. & Alexander, M., (2007). “Bond strength development between concretes of different ages”. Magazine of concrete research. 59(00).

Bissonnette, B. and others. (2008). “Concrete repair and interfacial bond: Influence of surface preparation”. Concrete Repair, Rehabilitation and Retrofitting: 2nd International Conference on Concrete Repair, Rehabilitation and Retrofitting, ICCRRR-2, 24-26 November 2008, Cape Town, South Africa. CRC. 345

Bonaldo E, Barros JAO, Lourenc- o PB.,(2004),”Bond characterization between concrete base and repairing SFRC by pull-off tests,” Report 04-DEC/E-13, University of Minho.

Dinis S. Santos, Pedro M.D. Santos, Daniel Dias-da-Costa.,(2012),” Effect of surface preparation and bonding agent on the concrete-to-concrete interface strength,” Construction and Building Materials 37 (2012) 102–110

Júlio, E.N.B.S., Branco, F.A.B. & Silva, V.D., (2004). “Concrete-to-concrete bond strength. Influence of the roughness of the substrate surface”. Construction and building materials. 18(9):675-681.

Martinola, G., Sadouki, H. & Wittmann, F.H., (2001). “Numerical model for minimizing risk of damage in repair system.” Journal of materials in civil engineering. 13(2):121-129

Perez, F., Morency, M., Bissonnette, B. & Courard, L., (2009). “Correlation between the roughness of the substrate surface and the debonding risk”. Concrete repair, rehabilitation and retrofitting II.

Silfwerbrand, J., (2003). “Shear bond strength in repaired concrete structures”. Materials and structures. 36(6):419-424.

Zhu, Y., (1992). “Effect of surface moisture condition on bond strength between new and old concrete”. Department of Strucutral Mechanics and Engineering, Royal Institute of Technology, Stockholm, Bulletin No. 159