Journal of Civil Engineering (IEB), 47 (1) (2019) 79-95

Journal of
Civil Engineering
IEB

Parameters affecting the interfacial bond between concrete of different ages: a review of literature

Arifur Rahman and Md. Mozammel Hoque

Department of Civil Engineering
Dhaka University of Engineering and Technology, Gazipur, Bangladesh

Received 30 May 2019

Abstract

This paper aims at reviewing the parameters that affect the bond at the interface between old and new concrete layers. The effective bond strength between these two different concrete layers ensures the monolithic action of the composite elements. The bond developed at the interface of old concrete layer to new concrete layer is influenced by several parameters: surface roughness, use of adhesives, shear connectors, moisture condition of substrate concrete, presence of micro-cracks, compressive strength of old and new concrete, the stress state at the interface and the amount of steel reinforcement crossing the interface. The influences of the parameters have been investigated by different researchers. In this paper, the influences of the parameters have been reviewed quantitatively. Both experimental and analytical investigations obtained from literature and different design specifications related to the strengthening of RC structural members have been presented. The present study represents useful information to the related individuals and professionals regarding the enhancing techniques of the interfacial bond between old and new concrete layers. The review results will enable the professional engineers to take appropriate steps to enhance the interfacial bond strength of RC composite members and especially the effectiveness of adopting RC jackets.

Keywords: Bond, Interface, surface roughness, adhesives, shear connectors, substrate, overlays.

1. Introduction

Large scale strengthening of reinforced concrete (RC) buildings are being executed all over the world to address the following cases; restorations, vertical extensions and/or horizontal expansions, change of structural functions and/or load(s), inferior quality of construction, to overcome the effect of improper structural design, deterioration of concrete due to aggressive environments, comply with recent code, age and so on. Different techniques of strengthening RC buildings are available in the literature (Pigeon et al. 1992, Talbot et al. 1995, Silfwerbrand, 2003, Julio et al. 2004, Santos et al. 2011). Most commonly used techniques adopted around the globe are: RC jacketing, Steel jacketing, FRP and/or CFRP jacketing, Ferro cement jacketing, etc. Some of the techniques involve large expense and rarely available materials in the local market while some others require highly technical personnel. Accounting for the material availability and techniques and technical personnel required for implementing the strengthening, RC jacketing is popularly being used all over the country especially in the developing countries. In RC jacketing, the repairing and/or strengthening structures involve overlaying new concrete with the required amount of reinforcement over existing concrete. Schematic presentation of RC jacketing of the column is shown in Figure 1.

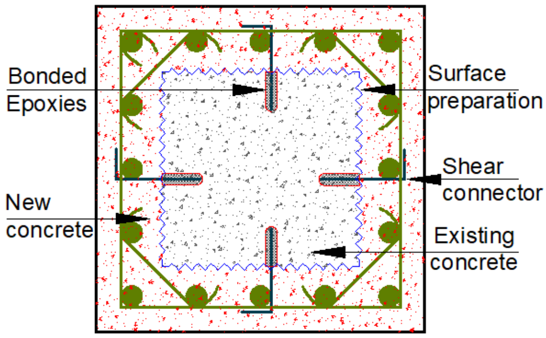

Fig. 1. Retrofitted reinforced column section.

The bond developed at the interface of old concrete to new concrete usually becomes the weakest link in the repaired/strengthened composite member as mentioned by Beaupre, 1994. The European Standard EN 1504-10 defined the bond strength as the adhesion of the applied product or system to the old concrete layer. In the literature (Pigeon et al. 1992, Talbot et al. 1995, Silfwerbrand, 2003, Julio et al. 2004, Santos et al. 2011) new concrete is termed as overlay while the old concrete is termed as substrate concrete. Proper bonding between substrate and overlay is one of the most important issues to ensure monolithic behavior of the composite member. Hence, ensuring proper bonding at the interface between substrate and overlay is a fundamental key to successful implementation strengthening. Apart from strengthening, bonding issue is also very important for a wide range of situations: precast beams with cast-in-place slabs, bridge decks strengthened by adding a new concrete layer, extensions and expansion of existing structures and so on. The present study would attempt to explore the effects of parameters affecting the interfacial bond strength and quantify the influence of different parameters with a view to obtaining the optimum combination parameters for achieving the maximum bond between old and new concrete.

2. Several parameters affecting the interfacial bond

The bond formed at the interface between two concrete layer cast at different times influenced by following several parameters: surface preparation, use of adhesives, shear connectors, moisture condition of substrate concrete, presence of micro-cracks, compressive strength of old and new concrete, the stress state at the interface and the amount of steel reinforcement crossing the interface. Each of the parameter acting with different degree of influence which is discussed in the upcoming sections.

2.1 Surface preparation

Substrate surface preparation of concrete significantly influences interfacial bond between substrate and overlay concrete. It is common practice to introduce different surface preparation techniques before applying overlay concrete. There are several surface preparation techniques that are introduced on the substrate surface: wire brushing, sandblasting, water jetting, chipping, grinding, shot blasting, etc. In Bangladesh, chipping method with metallic chisel is being used to make substrate roughen as a surface preparation technique before applying overlay concrete. In RC jacketing, the common practice consists of first increasing the roughness of the substrate concrete, overlay material are added placing required longitudinal and ties rebar then apply new concrete layer to change the section. The need to prepare substrate surface is addressed in all the published work in the literature (Pigeon et al. 1992, Talbot et al. 1995, Silfwerbrand, 2003, Julio et al. 2004, Santos et a., 2011). Several studies were conducted to quantify the effectiveness of the different of surface preparation techniques.

2.2 Use of bonding agents

Opinions (Emmons 1994, Austin et al. 1993, Cleland and Long 1997, Talbot et al. 1995, Julio et al. 2005) have diverged regarding the contribution of epoxy-based bonding agent on interfacial bond strength between the concrete of different ages. There are several published works on adhesion between substrate and overlay with bonding agents. Emmons 2012 has stated about bonding agents that it should be easily absorbed by the pore structure of the substrate and must be compatible with substrate and overlay. There are three main types of bonding agents that are frequently used: cement based slurries, epoxies, and latex emulsion. The author has figured out that adequate bond may be developed by placing overlay material directly against the prepared substrate concrete and the use of epoxy bonding agents may produce a vapour barrier which may result in de-bonding. Austin et al. 1993 have reported that bond coats can significantly increase the adhesion between different ages concrete, however, misuse can lead to much lower bond strength. Cleland and Long 1997, stated that the values of bond strength in tension are greatly reduced for some repairing material if no bonding agents are used. They concluded that the principal function of a bonding agent is to develop a bonding bridge between different ages concrete. Using bonding agent reduces the variability of results as stated by Talbot et al. 1995. In this connection, Julio et al.2005 investigated the contribution of bonding agents-epoxy resin considering different surface preparation techniques. The test results illustrated that the bond strength in shear and tension of the interface reduced when the epoxy resin was applied on the sandblasted surface, contrary to what happen when other roughening methods were used. However, the conclusions reached by several authors are not always the same. In addition, the results are not comparable, owing to the enormous variability of parameters that influence the interfacial bond and strength. Saucier and pigeon 1992 concluded that casting overlay directly on existing concrete is better than using cement-based slurry with high water to cement ratio as a bonding agent.

2.3 Moisture condition of substrate surface

In the literature (Talbot et al.1995, Zhu 1992, Silfwerbrand 2003, Julio et al. 2005 and Saucier and Pigeon 1992) moisture of the substrate concrete has been involved many controversial issues amongst the researchers. Talbot et al. 1995 reported that pre-wetting the surface (i.e., saturated with a dry surface) before applying the new concrete layer is the most appropriate solution. On the contrary, Zhu 1992, Silfwerbrand 2003, Julio et al.2005 and Saucier and Pigeon 1992 investigated the effectiveness of the substrate moisture. The test result reveals that the moisture content does not play a major role in affecting the bond strength of the repaired concrete specimen. The idea behind pre-wetting the substrate to a saturated surface dry state to enrich bond strength is misleading, and in many cases, results in lower bond strengths are obtained by Julio et al.2005. The added water potentially disturbs the interlocking capabilities of the substrate by limiting its capillary pore action with the overlay mix (Silfwerbrand 2003). In connection to, Silfwerbrand and Beushausen 2006, established a graph which best represented previous studies carried out in this regard. Figure 2 illustrates how the bond strength changes with respect to the substrate moisture condition. From figure 2, it is shown that bond strength reduced with increasing moisture in the substrate. The added water actually bother the interlocking abilities between old concrete and new concrete hence, the lower bond is obtained (Lukovic *et al.* 2012). In other words, although substrate pre-wetting may reduce bond strength to a certain extent, the imposed differential shrinkage between substrate and overlay due to excessive water lose in the overlay mix from substrate capillary action is of great concern. This differential shrinkage is reported to be the main aspects which lead to ultimate bond failure of repaired concrete (Santos *et al.* 2005, Lukovic *et al.* 2012). Finally, it can be summarized that the result of too dry or too wet surface runs the bond strength to weaken. Simon Austin and Peter Robins 1995, carried out an experimental investigation which results showed that the best result is when the substrate is saturated surface dry condition (SSD). Further investigations should be conducted on the issues of on the substrate moisture.

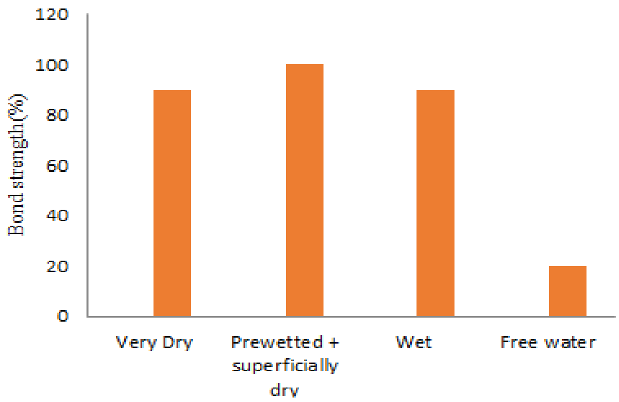

Fig. 2. Moisture condition and bond strength (Silfwerband and Beushausen, 2006).

2.4 Shear connectors crossing the interface

The amount of shear reinforcement crossing the interface of the substrate to overlay is an important parameter of shearing mechanism. The contributions of using shear connector at the interface of substrate to overlay have been scrutinized by several authors (Julio *et al.* 2004, Santos *et al.* 2011). Julio *et al.* 2004, performed push-off tests to quantify the influence of bond strength using shear connector on the interface. The obtained results were shown that added shear connectors at the interface didn’t significantly increase the de-bonding force but increase almost directly the longitudinal shear strength considering slipping between old concrete and new concrete.

2.5 Presence of micro-cracks

It has been well known that the bond enriches with increasing surface roughness (Talbot *et al.* 1995, Pigeon *et al.* 1992). However, making a surface very rough by metallic chisel is usually associated with formation of micro cracks which weakens the bond (Talbot *et al.* 1995). In addition, micro cracks causes reduction in the effective bond area. Hofbeck *et al.* 1969 mentioned that cracks along the shear plane outcomes in a reduction of the shear strength and in an increase of the relative slip between substrate and overlay concrete. Several researchers, such as Silfwerbrand 1990, Talbot *et al.* 1994 and Bissonnette *et al.* 2006, concluded that some removal techniques, such as hand-held hammers, can potentially generate micro-cracking in the substrate concrete and, therefore, can lead to lower bond strength.

2.6 Compressive strength of substrate and overlay material

The added concrete as well as substrate materials compressive strength influences interfacial bond strength. Julio et al. 2006 investigated the effect of compressive strength on bond strength between two concrete layers considering different mixtures of the added concrete with different strength. Experimental results reveal that increasing the overlay compressive strength relative to the substrate compressive strength improve the bond strength and change the rupture mode from adhesion to monolithic.

2.7 The stress state at the interface

The stress state at the interface significantly influences the interfacial bond of substrate to overlay concrete layer. In design code specifications (ACI 318 2008, BS 8110-1 1997, CEB-FIP 1990, EN 1992-1-1-Eurocode 22008), it has been observed that bond quantifying equations are based on stress state at the interface. The specification also added that the results obtained from different tests should be analyzed, interpreted and used very carefully, because in practical situations the interface is subjected to multi stress state of tension, shear and compression.

3. Interface load transfer mechanism

Shear forces transfer across concrete-to-concrete interfaces is crucial to the strength of strengthened or retrofitted reinforced concrete structures. The interface between existing deficient reinforced column and added concrete is an example where this concept might be considered. The characteristics of substrate to overlay concrete interface, subjected to external shear forces, can be predicted by shear-friction principle. As per the principle, when a joint between two rough surfaces is required to transfer shear forces, the shear will be resisted by friction resulting from an external force or from reinforcement crossing the interface shown in Figure 3. Therefore, it is assumed that the longitudinal shear reinforcement will compress the interface, resulting in frictional resistance along the interface. To exemplify the basic principles of this theory, a simple saw tooth model is used. The effects of booth shear reinforcement crossing the interface and normal stresses to the shear plane are considered.

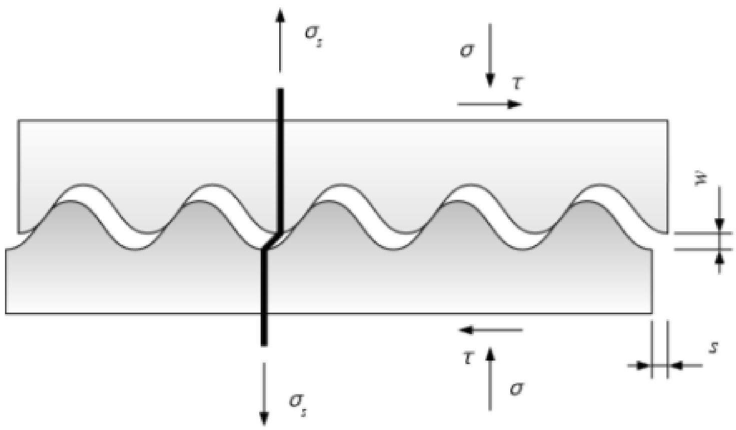

Fig. 3. Shear friction model.

Shear transfer at the interface of substrate to overlay concrete can be considered for two conditions; a). Interfaces shear strength without loss of adhesion and b) interface shear strength with relative slip between both concrete parts. It is to be mentioned that the shear friction theory only applicable for the second condition where the interfacial behavior is assumed to be controlled by cohesion, friction and dowel action. In opposition to the shear friction theory, Hsu *et al.* 1987 investigated shear transfer methodology across the interface and he proposed a shear transfer theory based on truss model where failure is caused by crushing concrete struts. A similar theory but applicable both initially cracked and un-cracked shear plan was proposed by Hwang *et al.* 2000. In connection to, Gohnert 2003, also proposed a theory for shear transfer at the interface of both cracked and un-cracked sections followed

Hwang *et al*.2000.Zilch and Reinecke 2001, investigated the interfacial shear transfer mechanism of subtract to overlay concrete illustrated in Figure 4. They mentioned that shear strength at a concrete to concrete interface can be explained by combinations of three load carrying mechanisms; a) adhesion b) shear friction and c) shear reinforcement.

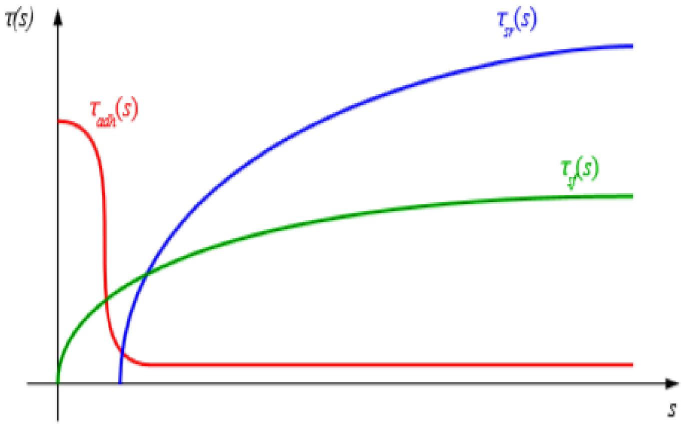

Fig. 4. Load transfer mechanism sustrate to overlay concrete interface by Zilch and Reinecke (2001).

Where, the adhesion component is originated by chemical bond connections between the particles of substrate to overlay concrete. De-bonding occurs at concrete to concrete interface when its maximum load carrying capacity is reached and shear stress will be transferred by mechanical interlocking. The shear stress will be transferred by shear friction if the interface is subjected to compression. With the increment of the relative displacement between concrete parts, the interface will be tensioned and yielding can occur. Therefore, the shear reinforcement will induce compression at the interface and the shear load will be will be transferred by friction. Due to slippage, the reinforcement will also be subjected to shear, usually termed as dowel action.

Table 3.1
Angle of friction according to BS 81110-1(1997)

Type of Surface	Tan α
Smooth interface	0.7
Roughen or castellated joint without continuous in situ strips across the end of joints.	1.4
Roughen or castellated joint with continuous in situ strips across the ends of joints	1.7

4. Shear strength capacity of interface

In the past decades, several experimental and analytical investigations have been suggested to quantify the interfacial bond strength by investigators. Regarding the most relevant studies, it is possible to summarize the one which were fundamental to develop designing models and some important research works. The followings are some of the proposed investigations.

4.1 BS 8110-1 (1997)

According to BS 8110-1(1997), the shear strength between substrate to overlay can be calculated as follows.

$$Vu = 0.6\ F_b\ \rho\ \tan\alpha \tag{1}$$

Where, F_b = minimum value between 0.95 fy As and the anchorage value of the reinforcement; fy = yield strength of the reinforcement; As = area of the shear reinforcement crossing the interface; ρ = the reinforcement ratio; and α = angle of internal friction between the faces of the joint. The value of α is already proposed for three different situations. This standard also recommend that the angle of internal friction should vary from 0.7 to 1.7.

4.2 Euro-code 2 (2004)

Euro-code 2 (2004) classified the prepared surfaces as very smooth, smooth, rough or intended based on their surface conditions which are obtained after preparation the concrete surface. The code recommends the following expression for evaluating the design shear stress at the interface of concrete of different ages can be calculated as follows.

$$\mathrm{Vu} = \mathrm{c}\ \mathrm{f_{ctd}} + \mu\, \sigma_n + \rho\, \mathrm{f_y}\ (\mu\ \sin\alpha \cos\alpha) \leq 0.5\ \mathrm{v}\ \mathrm{f_{cd}} \quad (2)$$

Where, c and μ = factors depends on interface roughness; f_{ctd} = the design tensile strength; σ_n = external normal stress acting on the interface; ρ=reinforcement ratio; α = the angle between the shear reinforcement and the shear plan; v= shear strength factor and f_{cd} = compressive strength of concrete.

4.3 CEB-FIP Model Code (1990)

According to the CEB-FIP model code, the shear stress at the interface of substrate to overlay concrete is followed as:

$$\mathrm{Vu} = \mathrm{cf_{ctd}} + \mu(\sigma_n + \rho \mathrm{f_y}) \leq 0.25\mathrm{f_{cd}} \quad (3)$$

Where, c and μ = factors depends on interface roughness; f_{ctd} = the design tensile strength; σ_n = external normal stress acting on the interface; ρ =reinforcement ratio (>0.1%); α = the angle between the shear reinforcement and the shear plan; v= shear strength factor; fy = yield strength of the reinforcement and f_{cd} = compressive strength of concrete. The interfacial shear strength of substrate to overlay can be calculated by a combination of three different carrying mechanisms; a) cohesion; b) shear-friction; c) shear reinforcement. The specification (CEB-FIP Model Code ,1990) also mentioned that the shear resistance of a concrete joint for a given slip can be calculated as the sum of each resisting mechanism. The coefficient of cohesion and friction given by this design code, for each type of surface preparation, presented below in Table 3.2.

In case of where shear reinforcement at the interface is considered lower and, no shear reinforcement is necessary, the CEB-FIP model code 1990 (1990) proposes that the shear stress at the interface of substrate to overlay, vu can be calculated only by

$$Vu = cf_{ctd} \quad (4)$$

And for plain interface, the design shear strength at the interface vu is given by

$$\mathrm{Vu} = \mu[\sigma_n + \rho \mathrm{f_y}(\sin\alpha + \cos\alpha)] \leq 0.3\mathrm{f_{cd}} \quad (5)$$

4.4 Anderson (1960)

Anderson (1960) was one of the first who proposed a design expression for quantifying the interfacial longitudinal shear strength of substrate to overlay. The proposed expression was as follows.

$$\mathrm{Vu} = \mathrm{v_0} + \mathrm{k}\rho \quad (6)$$

Where Vu = ultimate longitudinal shear stress at the interface; v_0 and k = two parameters obtained from push off test; ρ = reinforcement ratio. This expression was calibrated for two different low and high strength concretes with a compressive strength of 20.68Mpa (3000 psi) and 51.71(7500 psi). For the weakest concrete, the design expression is as follows.

$$\mathrm{Vu} = 4.41 + 229\rho \text{ (Mpa)} \tag{7}$$

In case of strongest strength concrete, the design expression is as follows.

$$\mathrm{Vu} = 5.52 + 276\rho \text{ (Mpa)} \tag{8}$$

Table 3.2
Coefficient of cohesion (c) and friction (μ) according to CEB-FIP model code 1990

Category	Type of surface	c	μ
Type-1 Smooth	I: a smooth surface obtained against steel or timber shutter	0.2*	0.6
	II: a surface lies between trowelled or floated to a degree		
	III: a surface lies between trowelled or floated with no small ridges, indentations or undulations		
	IV: a surface achieved by slip forming		
	V: a surface accomplished from extrusion		
	VI: a surface having deliberated textured by lightly brushing concrete		
Type-1 Rough	VII: as surface IV, with more pronounced texturing obtained by brushing, by a transverse screeder or by combining with a steel rake	0.4	0.9
	VIII: a surface having rough surface with coarse aggregate protruding.		
	IX: a surface exposing the coarse aggregate without disturbing		
	X: a surface achieved by mechanical shear keys.		

** Very smooth surfaces (Type I and II), it is recommended to the use of c=0.1.*

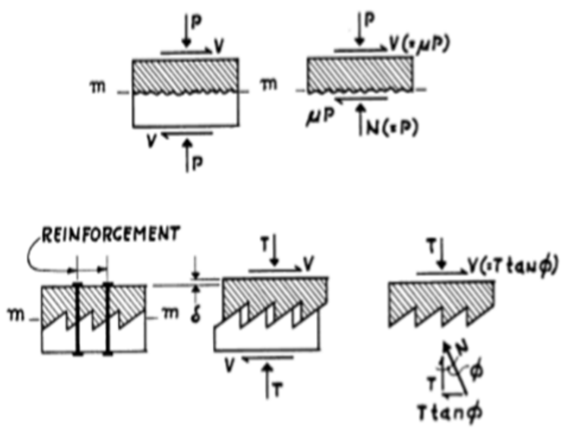

Fig. 5. Shear friction model.

4.5 *Birkeland and Birkeland (1966)*

Birkeland and Birkeland (1966) published an article presenting a design expression to predict the ultimate longitudinal shear stress at the interface of different age’s concrete. The proposed expression is as follows.

$$Vu = \rho f_y tan\Phi = \rho f_y \mu \tag{9}$$

This equation was proposed for the smooth concrete surface; artificial roughen concrete surface and concrete to steel interface. The value of coefficient of friction varies with surface preparation which empirically determined and this value was defined for several conditions, namely: a) μ = 1.7, for monolithic concrete (59.5º); b) μ = 1.4, for artificially roughened construction joints (54.5º); and c) μ = 0.8 to 1.0, for ordinary construction joints and for concrete to steel interfaces (38.7º to 45.0º).

For the first time it was explained the shear friction analogy. When a joint between two rough surfaces is required to transfer shear forces, the shear will be resisted by friction resulting from an external force or from reinforcement crossing the interface, is shown in Figure 4(a). Therefore, it is assumed that the longitudinal shear reinforcement will compress the interface, resulting in frictional resistance along the interface.

4.6 ACI 318 (2008)

ACI 318 (2008) proposes expression for evaluating the ultimate longitudinal shear stress at the different ages concrete interface can be calculated as follows.

$$\mathrm{Vu} = \rho f_y (\mu \sin\alpha + \cos\alpha) \quad (10)$$

Where, ρ=reinforcement ratio; α =the angle between the shear reinforcement and the shear plan; Vu= Interficial shear strength, fy= yeild strength of the reinforcement. The proposed design expression was suggested by Birkeland and Birkeland (1966). This code added the influence of the orientation of the shear reinforcement crossing the interface. The coefficient of friction μ is defined for four situations; a) concrete placed monolithically b) concrete placed against harden concrete with surface intentionally roughen c) concrete placed against harden concrete not intentionally roughen c) concrete anchor to as-rolled structural steel by headed studs or by reinforcing bar which are given following table.

Table 3.3
Coefficient of friction proposed by ACI 318-08

Type of surface	Coefficient of friction, μ
Concrete placed against harden concrete not intentionally roughen	0.60 λ
Concrete placed against harden concrete with surface intentionally roughen	1.00 λ
Concrete placed monolithically	1.40 λ
Concrete anchor to as-rolled structural steel by headed studs or by reinforcing rebar	0.70 λ

The parameter (λ is a modification factor related to concrete density and shall be taken equal to 1 for normal weight concrete;0.85 for sand light weight concrete and 0.75 for all light weight concrete.

5. Experimental results conducted by researchers

In literature, several tentative studies have been conducted to quantify the interfacial bond strength between substrate and overlay by several researchers. The following are the outcomes that obtained from some experimental investigations.

5.1 Garbaczet al. (2004)

Garbacz*et al.* (2004)studied the effect of substrate surface preparation on the interfacial bond between substrate and overlay concrete. In the study, different surface preparation techniques such as grinding (G), sand blasting (SB), shot blasting (ShB), hand- and mechanical milling (MH or MM) were performed. The parameters were surface geometry, superficial concrete micro-cracking and adhesion. The substrate concrete geometries were 300 mm x 300mm x 50mm. In experiment, the effect of eight surface preparation techniques with and without bond coat was evaluated. The adhesion was quantified by the pull-off test after 28 days of curing. Achieved results are shown in table 4.1. The investigation exhibited that the adhesion in repair system is a complex phenomenon and test results revealed that the interfacial bond strength were greatly depends on the effect of the surface roughness of substrate concrete, the presence of micro cracks in the near-surface layer and deteriorated grains of aggregate as well as processing properties of the repair materials including interfacial tension between the bond coat and/or repair materials. The interfacial bond strength were increase of -5.21%, 0.52%,-12.50%, 1.04%, 2.08%,-26.04% and -16.67% with bond coating specimens and -49.12%, -20.18%,-65.79%, -45.18%, -63.60%,-55.70% and -78.51% without bond coating specimens for G,SB,ShB(20s), ShB(35s), ShB(45s), MH and MM with compared to as cast techniques. It is also noted that shot blasting and milling generate more cracks and any increase in duration of the treatment induces higher deterioration of the near-surface layer.

Table 4.1
Interfacial bond strength from pull off test

substrate surface treatments	Interfacial bond, MPa with bond coat		Interfacial bond, MPa without bond coat		
	A	*	C	*	A/C
As cast (Ref.)	1.92	N/A	2.28	N/A	0.84
G	1.82	-5.21	1.16	-49.12	1.57
SB	1.93	0.52	1.82	-20.18	1.06
ShB (20 s)	1.68	-12.50	0.78	-65.79	2.15
ShB (35 s)	1.94	1.04	1.25	-45.18	1.55
ShB (45 s)	1.96	2.08	0.83	-63.60	2.36
MH	1.42	-26.04	1.01	-55.70	1.41
MM	1.6	-16.67	0.49	-78.51	3.27

** represents the % of increment/decrement of bond strength*

The surface roughness and the presence of bond coat have an effect on the type of failure. Cohesion failure is more frequent in the case of the use of a bond coat and is directly influenced by the micro cracks.

5.2 Julio et al. (2005)

Julio *et al.* (2005) evaluated the effect of different substrate surface preparation on the interfacial bond considering following techniques: wire-brushing; sand-blasting; chipping with a light jackhammer; left as-cast against steel formwork. Interfacial bond strengths illustrated in Table 4.3, were evaluated by Slant shear test and Pull off test. The geometries of the specimen were 200mm x 200mm x 400mm prism with the 30 degree inclination to the vertical and pull off specimen was 200mm cube with the interface line at the middle. On the substrate specimens following surface preparation techniques were introduced interlocking substrate to overlay concrete, illustrated in Figure 6. The experimental results obtained from Slant shear test were revealed that superior bond strength was found 14.13 MPa for sand blasting technique and where lower bond strength was found 1.30 MPa for specimens that were as cast against steel formwork. In case of Pull of test, superior and inferior bond strength was found for the same surface technique of sand blasting and as cast against steel formwork. Additionally, it should be mentioned that the rupture mode, observed in all specimens tested with both methods were an adhesive failure.

5.3 Julio et al. (2006)

Julio *et al.* (2006) performed an investigation to evaluate the influence of the overlay concrete compressive strength on the interfacial bond strength between substrate and overlay concrete of different ages, considering different overlay concrete mixtures. The specimens first had the substrate roughness by sand blasting surface preparation technique. Later on, the overlay concrete of three different mixtures was added on the substrate concrete. Three different situations were considered where substrate compressive strength was unchanged of 30 MPa and overlay compressive strength were varied to 30 MPa, 50 MPa and 100 MPa, respectively. To quantify interfacial bond strength, Slant shear test was carried out. The adopted geometries of Slant Shear specimen were 200mm x 200mm x 400mm prism with the shear plan 30 degree to the vertical. The details of the specimens were shown in Figure 7.

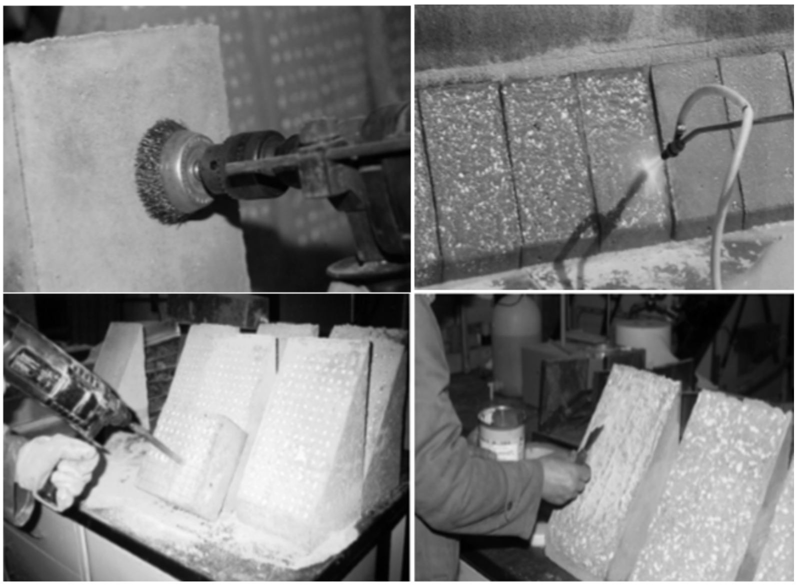

Fig.6. Details of surface preparation techniques:
(a) wire brushing (b) sand blasting (c) Chipping (d) chipping with epoxies.

Table 4.3
Slant shear test and pull of test results

Surface preparation technique	Interfacial bond strength			
	Slant shear test, Mpa(Psi)	Variation coefficient %	Pull off test Mpa(Psi)	Variation coefficient %
As cast against steel formwork (ref.)	1.30 (188.5)	33.85	--	-
Partially chipped	6.24 (904.8)	20.67	1.47 (213.15)	7.48
Wire brushing	10.67 (1547.15)	8.90	1.92 (278.4)	13.54
Sand blasting	14.13 (2048.85)	8.56	2.65 (384.25)	6.42

The experimental result indicated that increasing the compressive strength of the overlay concrete relative to the compressive strength of the substrate concrete improves the interfacial bond strength and change the rupture mode from adhesive to cohesive (monolithic). It is also found that interfacial bond strength was found increase of 13.07% and 24.83% compared to 30/30 specimen.

5.4 Santos and Júlio (2011)

Santos and Júlio (2011) investigated the influence of the substrate surface preparation on concrete-to-concrete interfaces. As cast (AC), wire-brushing (WB), sand blasting (SB), shot blasting and hand scrubbing techniques were used as surface preparation techniques to make substrate surface roughening. To quantify interfacial bond strength, Slant shear test and Splitting test were carried out. The adopted geometries were 150mm x 150mm x 450mm prism with the shear plan 30 degree to the vertical and 150 mm cube with the interface at middle height for Slant shear test and Spiriting test, respectively. The details of the specimens were shown in Figure 8.

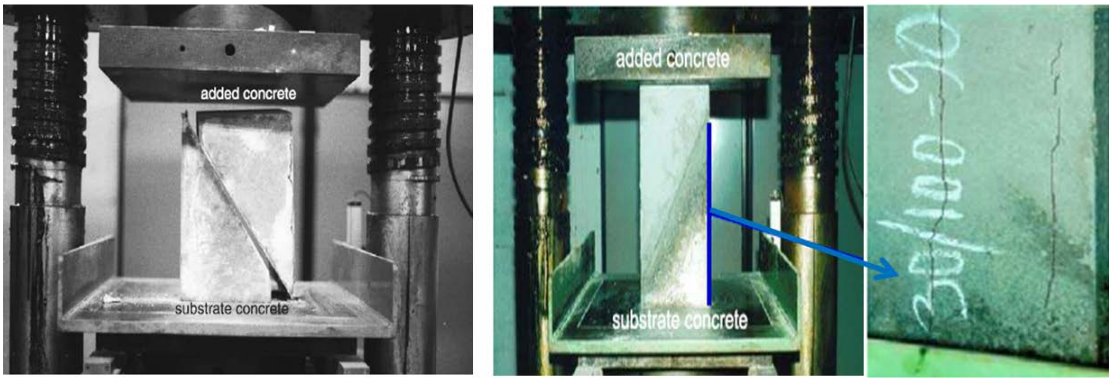

Fig. 7. a) Adhesive rupture mode of 30/30 Slant shear specimens
b) monolithic rupture mode of 30/50 and 30/100 slant shear specimens.

Table 4.2
Interfacial bond strength from slant shear test

Test name	specimen ID	Comp. strength of Substrate, MPa	Comp. strength of Overlay, MPa	Bond Strength MPa	increment of bond strength, %
Slant shear Test	30/30	37.73	35.37	13.01*	N/A
	30/50	33.53	45.61	14.71**	13.07
	30/100	33.09	91.25	16.24**	24.83

and denotes adhesive and monolithic failures, respectively.*

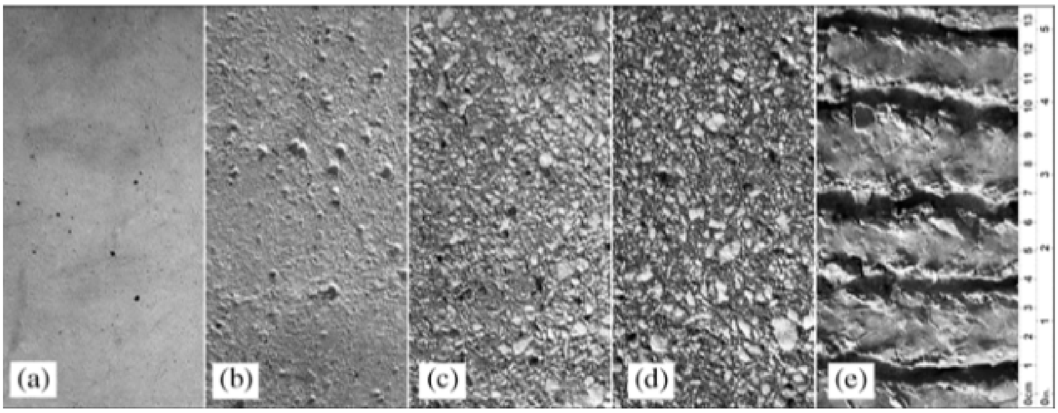

Fig. 8. Surface preparation: (a) left as-cast (b) wire-brushing (c) sand blasting
(d) shot blasting and (e) hand-scrubbing(HS).

The experimental result revealed that the superior bond strength was observed for the hand scrubbing surface preparation technique in both two Slant shear and Splitting tests. The obtained results also pointed out that interfacial bond strength were increased of 2.59%, 10.52%, 2248% and 49.78% in Slant shear test and 5.73%, 18.23%, 28.13% and 54.69% in Splitting test for As cast, wire brushing, sand blasting, shot blasting and Hand scrubbing surface preparation techniques compared to as cast surface preparation technique. It is also to be noted that two types of adhesive (interface deboning) and cohesive (monolithic) failures were observed. In Splitting test, all specimens presented adhesive failures and in Slant shear test, the number of cohesive failures Figure 9 increased with the increase of the surface roughness of the interface.

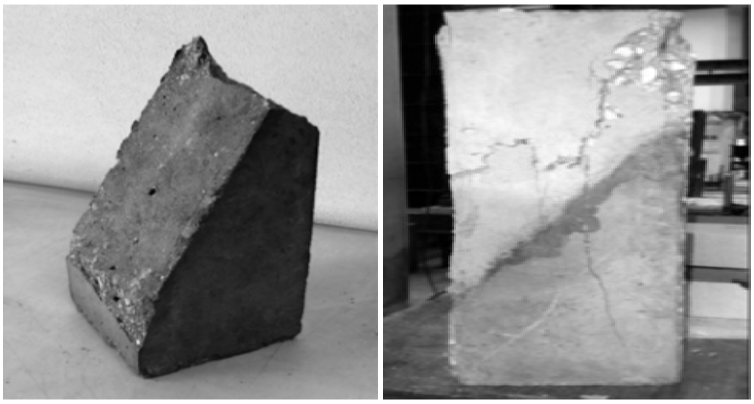

Fig. 9. Failure modes for slant shear test: (a) adhesive and (b) cohesive.

Table 4.4
Interfacial bond strength (slant shear and splitting)

Test name (Test conducted at 84 Days)	Surface treatment	Avg. bond strength, MPa	COV%	% increment
Slant shear test	As cast (ref.)	13.88	11.04	N/A
	WB	14.24	20.59	2.59
	Sand blasting	15.34	28.56	10.52
	Shot Blasting	17	18.44	22.48
	Hand Scrubbing	20.79	7.29	49.78
Splitting Tensile test	As cast (ref.)	1.92	8.51	N/A
	WB	2.03	15.03	5.73
	Sand blasting	2.27	14.67	18.23
	Shot Blasting	2.46	19.04	28.13
	HS	2.97	15.48	54.69

5.5 Tayeh et al. (2012)

Tayeh *et al.* (2012) conducted an experimental investigation on the effect of substrate surface preparation on the interfacial bond between substrate and overlay concrete. As cast (AC), wire-brushed (WB) and sand blasted (SB) techniques were used as surface preparation on the substrate concrete. Introduced roughness was determined using an optical three dimensional surface metrology device. In the study interfacial bond strength were evaluated by pull-off test (ASTM D4541), splitting cylinder tensile test (ASTM C496) and the slant shear test (ASTM C882). The specimen's geometries were 300 mm x 300mm x 80mm slab, 100mm diameter x 200mm height cylinder and 100mm x 100mm x 300mm prism with the 30 degree inclination to the vertical for Pull off, Splitting and Slant shear test, respectively. The details of the specimens were illustrated in Figure 10. The experimental results revealed that the superior bond strength was found for the sand blasting technique whereas inferior bond strength obtained for as cast surface techniques in all the three different tests. The bond strengths were increased of 0.87%, 1.74% in Pull off test; 60%, 104.89% in splitting test and

46.89%, 105.18% in Slant shear test for wire- brush and sand blasting techniques compared to as cast surface preparation techniques, respectively.

Fig.10. Details of surface preparation techniques.

Table 4.5
Pull of test, splitting test and slant shear test

Test results at 28 days				
Test name	Surface treatment	Avg. bond strength, MPa	% increment	Failure mode
Pull-off test	As cast (ref.)	2.3	N/A	substrate
	Wire brushing	2.32	0.87	substrate
	Sand blasting	2.34	1.74	substrate
Splitting Tensile test	As cast (ref.)	1.85	N/A	substrate
	Wire brushing	2.96	60.00	substrate
	Sand blasting	3.79	104.86	substrate
Slant shear test	As cast (ref.)	8.68	N/A	substrate
	Wire brushing	12.75	46.89	substrate
	Sand blasting	17.81	105.18	substrate

5.6 Chilwesa et al. (2016)

Chilwesa *et al.* (2016) conducted an experimental study to evaluate the effect of substrate roughness on the interfacial bond strength along with the effect of overlay strength through a newly developed indirect test method. In literature (Mehta and Monteiro, 2006; Neville, 1996), direct tensile strength tests are complicated to perform due to difficulties associated with the holding mechanisms at the specimen ends which lead to high stress concentrations and thus premature specimen failure. Consequently, an indirect test method, the flexural test, was developed evaluating the tensile strength/ interfacial bond strength. Details of the test method are illustrated in Figure 4(e). As cast on wooden formwork, wire brush and grooved surface (Cutting grooves of 5 mm deep and 5 mm wide, over a 100 mm length of the substrate surface) techniques were used to obtain different roughness indexes.

In study, three types of overlay materials having compressive strength of normal-strength concrete (NSC) [20–50 MPa], high-strength concrete (HSC) [51–120 MPa] and very high strength concrete (VHSC) [>120 MPa] were chosen for the investigation. Ingredients of the specimens were shown in Table 4.6. The specimens consists of two 200m x 100mm x 100mm substrate prism to two ends, on the sides of which are cast 400mm x 100mm x 100mm overlay prisms such that four contact areas are created between two materials and 100 x 100 mm^2 each contact area. Details of the specimens are shown in Figure 11.

Table. 4.6
Ingredient of the specimens

Ingredients	Substrate	Three type Overlay concrete		
		NSC	HSC	VHSC
Strength, MPa	35	20-50	51-120	>120
W/C: kg/m^3	0.45	0.48	--	--
Cement: kg/m^3	330	376	--	--
Water: kg/m^3	185	180	--	--
Gravel: kg/m^3	845	851	--	--
Sand: kg/m^3	1033	1041	--	--
Super-plasticizer : kg/m^3	900	1200	--	--
Slump: mm	85	85	105	105
Comp. strength at 28 days, MPa	36	41	66	127

Fig. 11. Specimens' details.

Table 4.7
Interfacial bond strength from newly developed test

Techniques	Interfacial bond, MPa	% of bond increment
As cast against wooden formwork (ref.)	1.93	N/A
Wire brush	2.29	18.65
Grooved	2.51	30.05

The experimental outcomes demonstrated that interfacial bond strength greatly influenced by the substrate roughness. Bond strength increased with the increment of the substrate roughness. The overlay strength was additionally observed to be an imperative parameter that influenced the interfacial bond. It is noted that interfacial bond strength were increased of 18.65% and 30.05% for the wire brushed and grooved specimens compared to the as cast specimens against wooden formwork.

6. Conclusions and recommendations

This study intends to provide the information to the professional engineers and academicians related to bond at the interface of concrete cast at different times. In this regard, related literatures have been studied and different design equations for instance BS 8110-1 (1997), Euro-code 2 (2004), CEB-FIP Model Code (1990) and ACI-318 (2008) as well as investigations conducted by researchers have been reviewed. It has been found that Euro-code

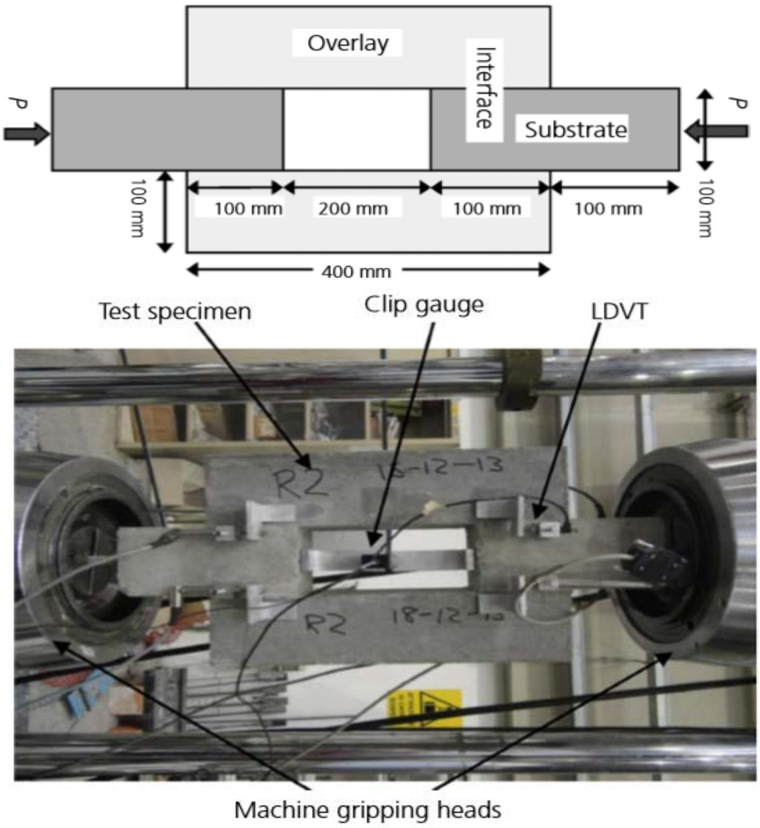

Fig. 12. Newly developed machine details.

2 (2004) and the ACI 318 (2008)emphasis on four basic parameters that greatly affects the interfacial bond strength which are compressive strength of the weakest concrete, normal stress at the interface, amount of the shear reinforcement crossing the interface and substrate surface preparation. However, shear connectors and surface roughness seems to be the main influential parameters. Surface preparation of the substrate concrete increases the interlocking phenomenon between two concrete layers therefore bond strength is increased. The interfacial bond strength is also improved with increment of the compressive strength of the overlay concrete compared to substrate concrete consequently rupture mode is changed from adhesive to monolithic. Based on the review, experimental investigation can be done to quantify the effect of parameters which are greatly used in Bangladesh.

References

A. Garbacz, M. Gorka and L (2004). "Courard. Effect of concrete surface treatment on adhesion in repair systems", Magazine of Concrete Research. Vol. 56(00).

ACI 318 (2008) "Building code requirements for structural concrete" , (ACI 318-08) and commentary, Committee 318, American Concrete Institute, PO Box 9094, Farmington Hills, MI 48333-9094, USA, 471 p.

Anderson, A.R.(1960) "Composite designs in precast and cast-in-place concrete", Progressive Architecture, 41(9), 172-179.

ASTM C 882(1999), "Standard test method for bond strength of epoxy-resin systems used with concrete by Slant Shear," American Society for Testing Materials, USA.

ASTM C 1583 (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 Materials, USA.

ASTM C 496 (2004), "Standard test method for Splitting Tensile Strength of cylindrical concrete specimens," American Society for Testing Materials," USA.

Austin S., Robins P. and Pan Y (1995) "Tensile bond testing of concrete repairs". Materials and Structures, RILEM, 28(179), 249–259.

Bassam A. Tayeh, B.H. Abu Bakara, M.A. Megat Joharia and M.M. Ratnamc (2012), "The relationship between substrate roughness parameters and bond strength of ultra-high-performance fiber concrete", 27 (16), 1790–1810.

Birkeland, P.W. and Birkeland, H.W (1966)."Connections in precast concrete construction, American Concrete Institute", Journal of the American Concrete Institute, 63(3), 345-368.

Bissonnette, B., Courard, L., Vaysburd, A.M. and Bélair, N. (2006) "Concrete removal techniques". Influence on residual cracking and bond strength, American Concrete Institute, Concrete International, 28(12), 49-55.

BS 8110-1 (1997) "Structural use of concrete", Part 1: Code of practice for design and construction, British Standard Institute, London.

C. Talbot, M. Pigeon, D. Beaupre, and D. R. Morgan (1995), "Influence of surface preparation on long-term bonding of shortcrete," ACI Mater J. 91(6), 560–566.

CEB-FIP Model Code (1990) for concrete structures, Comité Euro-International du Béton, Secretariat Permanent, Case Postale 88, CH-1015 Lausanne, Switzerland, 437 p.

Chilwesa, M, Reggia, A, Minelli, F, and Plizzari,G (2016). "Evaluating the shear bond strength between old and new concrete through a new test method", Magazine of Concrete Research. 69(9), 425-435.

Cleland DJ; Long AE. (1997) "The pull-off test for concrete patch repairs". In: Proceedings of the Institution of Civil Engineers – Structures and Buildings.122, 451–60.

Emmons PH. (1994). "Concrete Repair and Maintenance" In: Part Three: Surface Repair, Section 6: Bonding Repair Materials to Existing Concrete. MA: R.S. Means Company; 154–63.

EN 1992-1-1 - Eurocode 2(2004)–"Design of concrete structures" - Part 1-1: General rules and rules for buildings, European Committee for Standardization, 225p.

Hofbeck, J.A., Ibrahim, I.O. and Mattock, A.H. (1969) "Shear transfer in reinforced concrete", American Concrete Institute, Journal of the American Concrete Institute, Vol. 66(2), 119-128.

Júlio, E., Branco, F. and Silva, V (2005)"Concrete-to-concrete bond strength: influence of an epoxy-based bonding agent on a roughened substrate surface", Magazine of concrete research.57 (8), 463-468.

Júlio, E.N.B.S., Branco, F.A.B. and 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.

Júlio, E.N.B.S., Branco, F.A.B. and Silva, V.D, Lourenco, (2006) JF. "Influence of added concrete compressive strength on adhesion to an existing concrete substrate", Building and Environment. 18(9), 675-681. 2006.

Lukovic, M., Savija, B., Ye, G. and Zhou, J. (2012). "Modelling water absorption of the concrete substrate in concrete repairs", (Concrete Repair, Rehabilitation and Retrofitting III – Alexander et al. (eds)).

Pedro M D Santos and E N B S Júlio(2011). "Factors Affecting Bond between New and Old Concrete" ACI Materials Journal, 108 (4).

Pigeon, M. and Saucier, F (1992)." Durability of repaired concrete structures" Advances in concrete technology, Ed.by VM malhotra, 741-773.

Santos, P.M.D."Influence of the surface roughness of the interface concrete/concrete in its longitudinal shear resistance", MSc Thesis, University of Coimbra, 2005, 202 (in Portuguese).

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 Structural Mechanics and Engineering, Royal Institute of Technology, Stockholm, Bulletin No. 159.