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Bond strength between stell-concrete and between concretes with different ages in structural rehabilitation

Aderência aço-concreto e entre concretos de diferentes idades em recuperação de estruturas



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Abstract

In inspections of buildings, it is common to find structures that, well before reaching its useful life longer require repairs and reinforcements. This study examined the bond strength between concrete of different ages and between steel and concrete, focusing on the recovery of reinforced concrete structures. To analyze the bond between concrete of different ages, trials with specimens receiving three different types of treatments at the interface between the concrete were performed: brushing; brushing and mortar equal to concrete of substrate and brushing and epoxy layer. Indirect tensile tests and oblique and vertical shear tests at the interface were made . The bond stress between steel and concrete was evaluated by pull out test under the conditions of the bar inserted in the still fresh concrete and when inserted in the hardened concrete with epoxy. Results showed increased bond strength by indirect tensile stress of 15% and 37%; 4% and 12% for the adherence test by oblique shear, and 108% and 178%, for the testing of vertical shear, respectively, for the specimens whose interfaces have received, in addition to brushing, layer of mortar and epoxy bridge, compared to those who received only brushing. Insignificant loss (about 0.52%) of bond stress was noticed for pull out test of steel bar when compared with test results of the specimens that had steel bar inserted in the concrete in the hardened state with epoxy adhesion bridge, with those who had inserted steel bar in fresh concrete.

Keywords: concrete structures, recovery materials, bond strength.

Resumo

Em inspeções de construções, é comum encontrar estruturas que, muito antes de atingirem sua vida útil, já necessitam de reparos e reforços. O presente trabalho analisou a resistência de aderência entre concretos de diferentes idades e entre aço e concreto, visando à recuperação de estruturas de concreto armado. Para análise da aderência entre concretos de diferentes idades, foram realizados ensaios com corpos de prova que receberam três tipos de tratamentos distintos na interface entre os concretos: escovação; escovação e camada de argamassa igual à do concreto de substrato e escovação e camada de epóxi. Foram feitos ensaios de tração indireta e cisalhamento oblíquo e vertical na interface. Foi avaliada a aderência entre aço e concreto, por ensaio de arrancamento, nas condições da barra inserida no concreto ainda fresco e quando inserida no concreto endurecido, com ponte de aderência de epóxi. Os resultados dos ensaios de aderência dos corpos de prova de concreto mostraram aumento na resistência de aderência por tração indireta de 15% e 37%; de 4% e 12%, para o ensaio de aderência por cisalhamento oblíquo, e de 108% e 178%, para o ensaio de cisalhamento vertical, respectivamente, para os corpos de prova cujas interfaces receberam, além de escovação, camada de argamassa e ponte de epóxi, em relação àqueles que somente receberam escovação. Percebeu-se, no ensaio de arrancamento de barra de aço, perda insignificante (cerca de 0,52%) na aderência, quando compararam-se os resultados dos ensaios dos corpos de prova que tiveram a barra de aço inserida no concreto no estado endurecido com ponte de aderência epóxi, com os que tiveram a barra inserida no concreto no estado fresco.

Palavras-chave: estruturas de concreto, materiais de recuperação, aderência.

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1. Introduction

As Mehta & Monteiro [1], it can be said that concrete is the building material most consumed worldwide. Its application is quite old and its composition almost did not undergo major changes over time. Thus, it is possible to conclude that, for its wide application and relatively little compositional variability over the years, the concrete execution technique should be well established as to obtain almost perfect structures. However, what is seen in the practical environment is increasingly common appearance of damages in concrete structures and their early degradation, often making necessary to restrict the use or demolish the structure.

According Helene [2], Portland cement concrete has proven to be the most suitable construction material for structures with advantages in relation to other building systems such as wood, steel and masonry. However, since the first evidence of use, the concrete is subjected to various mechanical loads and environmental aggressions, leading to high incidence of pathological manifestations, which are accompanied by high recovery costs.

In a concrete structure recovery that requires good adhesion between concrete of different ages, it is important to have knowledge about the factors that influence the interfacial strength between substrate concrete and concrete for recovery. The incompatibility of deformations between concretes with different ages creates tensions in the connecting interface, particularly those generated by differential shrinkage. In some situations where there is need for steel reinforcement replacement or complementation, the transfer of efforts between steel and concrete and the compatibility of deformations between these materials, guaranteed by the adhesion between the two materials, are important to the performance of the reinforced concrete structure. According to Neville and Brooks [3], the bond strength between reinforcement and concrete comes mainly from friction and adhesion and is affected both by the properties of steel as those of concrete and the relative movement due to volume changes, such as concrete shrinkage.

Souza & Ripper [4] relate that loss of adhesion can happen between two concrete of different ages, in interface between two different concretes, or in the contact between steel bar and concrete. This effect can be quite harmful and can lead to poor performance of the structure. Thus, it becomes important that experimental studies show the importance and effectiveness of the specific treatments of interface in concrete recovery, as well as between the steel and concrete, to achieve adequate adhesion between these materials in recovery services and strengthening of reinforced concrete structures.

1.1 Bond strength between concretes of different ages

Dimensional compatibility between concrete from repair and substrate is related to the ability of recovery material to distribute tensions at the contact surface, which are caused by different deformations of materials, without detachment or cracking in repair layer, after Li & Li [5]. The lack of dimensional compatibility is cited as one of the leading causes of premature failure of the repaired structure, which can generate repair durability problems. Beushausen & Alexander [6] state that is common for union of concretes of different ages, occurring during repair of concrete structures, and at the junction of precast concrete elements. Cánovas [7] refers to usual situation where there is bond between concrete of different ages, in the joints of concrete which occur in practice, in a planned manner, or by involuntary interruptions. The interval between the casting of first and second concrete can be several hours or even days. According Beushausen and Alexander [6], just an overlap of concrete with different age can lead to cracking and detachment in elements that was intended to unite. The causes that lead to inefficiency of this union are related to several factors such as the preparation of the substrate surface, the method of applying the newest concrete, curing procedure and even environmental factors. However, the main negative influences for the failure of link between old and new concrete is unsuitable execution of connection and differential shrinkage between new and old concrete.

Bissonnette et al. [8] stated that the preparation of surface where there will be the union between old concrete and new concrete is one of the key issues for obtaining high quality in this type of connection. The proper preparation of the surface is not limited to the processes that occur immediately before application of new concrete. Procedures such as cleaning of the surface, concrete casting and cure must be thoroughly conducted, so that bond strength is developed sufficiently in order to provide the stresses accommodation.

According to Alexander & Beushausen [6], bond strength is made by mechanical interaction, besides thermo-dynamical and chemical mechanisms. It is important to know that mechanical bond differs significantly from shear strength. For example, high roughness at the interface can enhance shear strength, though the bond strength depend mainly on the transverse anchoring in the pores and voids.

Courard et al. [9] refer to surface treatments on the concrete substrate to promote the mechanical interlocking. The most commonly used treatment is to increase the surface roughness by different methods abrasion. However, for very aggressive methods, there may be some undesirable side effects, especially the development of micro cracks within the substrate. In this experiment, authors have found evidence that, for concrete with compressive strength less than 30 MPa, there is increase of bond strength between original concrete and new concrete, if surface is prepared with sand blasting process and hydro-demolition. However, more aggressive treatments such as polishing and surface drilling led to significant loss of bond strength, which did not occur with stronger concrete. Thus, it can be said that concrete compressive strength is an important parameter for choosing the type of surface treatment, in order to obtain bond strength between concrete of different ages.

Bissonnette et al. [8] assert that there is extensive research related to factors that affect the bond between concrete substrate and repair material. In order to obtain results that can be quantified, it is necessary bond strength test and, therefore, a large number of tests have been developed. Tests analyze the performance under tensile forces, shear and various combinations of tension and compression. The predominant test is the pull out test, however faults may occur in the substrate concrete, interface or recovery layer. When the damage does not occur in interface, test result will only be a lower limit for bond strength.

As Beushausen [10], the connecting elements to improve interface between new and old concrete ranging from ready-made products until cement mixtures produced in situ. Despite the variety of products for connecting bridges between new concrete and old concrete, the efficiency of these products is still a subject much

debated among researchers and practitioners. Conflicting opinions also exist as to the possibility of positive influence on the bond strength when making wetting of concrete substrate. The author found that when comparing the bond strength between a substrate prepared by pre-wetting and another that was dry, there was no significant increase in adhesion and, in some cases, there was significantly lower strength values, when the surfaces were saturated. This can be explained by the fact that, when the substrate is dry, there is a better penetration of fresh concrete or bonding material into unsaturated pores of substrate concrete.
According to Brazilian standard NBR 14931: 2004 [11], ready-made products can be used to improve the adhesion between concretes of different ages, since they do not cause damage to concrete and demonstrate performance at least equal to the interface produced by usual methods. If resins will be used one should check its burning behavior.
Cánovas [7] mentions a study in Eduardo Torroja Institute, Madrid, Spain, where the use of epoxy resin as bonding bridge between concrete of different ages took to get a bonding with 100% efficiency, making structure fully monolithic.

1.2 Bonding between steel and concrete

In a reinforced concrete structure, the bond strength between concrete and steel is as important as the compressive strength of concrete. According to Neville [12], bonding between concrete and steel is important both in terms of structural behavior as in relation to cracking caused by shrinkage and thermal effects at early ages.
According to Araújo et al. [13], it is usual the separation of bond strength in three parts, as adhesion, friction and mechanical interaction. This classification is based on stress vs displacement curves. Adhesion is the chemical union, friction arises when there is movement between the materials and the mechanical grip relates to mechanical gearing.
However, these authors assert that the separation of bond strength in these three parts is only schematic due the impossibility to assess each one. This is justified by the fact that even a steel bar having smooth appearance may provide mechanical adhesion, depending on the surface roughness due to corrosion and manufacturing process that can produce ledges on the surface.
Tower-Casanova et al. [14] affirm that the main characteristics that influence the bond strength are the type of concrete used (geometry of aggregates, supplementary cementing materials, fibers), geometry of steel bars and loading parameters.
Besides those features, Soylev & Francois [15] indicate the position of steel bars and the method for compacting concrete as influencing factors of steel-concrete bond, but the ratio water/cement ratio (w/c ratio) is highlighted as the main factor influencing bond strength. Therefore, the authors proposed an experiment in which steel-concrete bond strength was measured with steel bar positioned horizontally in the concrete, simulating what occurs in slabs, in practical environment. It was observed that, for concrete with high w/c ratio, voids arose around steel bar, making weaker the bond strength to at these points. Five concrete samples were studied, with w/c ratio of 0.75, 0.53, 0.60 and 0.39, the latter being used for conventional and self-compacting concretes. The results showed that only the samples with w/c ratio of 0.39 showed no segregation. The best bond performance was obtained with the self-compacting concrete. As Neville [12], various factors may promote bond strength, such as the shrinkage of concrete in relation to steel, the geometry and surface texture of steel bar. The presence of rust on the steel bars favors the adhesion, while coating by galvanizing or epoxy resin impairs the steel-concrete bond.
According to brazilian standard NBR 6118: 2014 [16], the anchorage due to adherence occurs when efforts are supported by means of a straight length or by a large curvature radius, followed or did not followed by hook. This length is called “anchoring length” and it is important to have a sufficient size so that occurs the transfer of the bar’s efforts for concrete. The standard also shows formulas for calculating the bond strength and anchorage length required to allow that steel and concrete to act together.

2. Experimental program

Bond strength tests were carried out between concretes of different ages on different mechanical stress conditions, such as tensile stress under diametric compression, shear stress at 45º and vertical shear stress. Measurement of bond strength between concrete and steel was made by pullout test. Table [1] summarizes the amounts of specimens for each type of test and treatment of contact surface. Beushausen & Alexander [6] stated that when assessing the bond strength values between concretes, it is important to consider the stress state of the interface caused by the test method, which may represent the main stress state found in

Table 1 – Number of specimens for test type

Interfacial treatment		Bond strength test techniques			
		Indirect tensile	Oblique shear	Vertical shear	Pull out
Concretes with diferente ages	Bru1	4	4	3	–
	Bru/Mor[2]	4	4	3	–
	Bru/Epx[3]	4	4	3	–
Steel-concrete	Stl Mold[4]	–	–	–	4
	Hole/Epx[5]	–	–	–	4

[1] Brusing; [2] Brushing and mortar; [3] Brushing and epoxy; [4] Steel bar inserted into the molding; [5] Drilling and epoxy.

structure. However, due to variety of stress states that can cause loss of bond between the materials, it is difficult to choose the method that best represents the condition of given structure, leading to often be the chosen the method for which there is available equipment.

Aimed at finding the most appropriate method for evaluating the bond strength between substrate concrete and materials for structural recovery, Momayez et al. [17] developed a comparative study on the main bond strength tests between concretes. Test methods applied in the present study were based on methods from the cited study. According to these authors, to measure the adhesion between concretes of different ages, the tests that presented the best results, based on lowest coefficient of variation and lower level of execution difficulty, were the oblique shear tests, followed by vertical shear tests, concluding that the bond strength test by indirect traction was the least efficient.

In this study, two types of concrete were used, named substrate concrete, with mass proportions 1.00: 1.74: 2.37 and w/c ratio of 0.45; and recovery concrete, with mass proportions 1.00: 1.56: 1.85 and w/c ratio of 0.40. A characteristic compressive strength (f_{ck}) of substrate concrete was specified to 30 MPa with slump of 80 mm. Recovery concrete was a self-compacting concrete (scc) with f_{ck} of 35 MPa. Silica fume was applied as 12.5% ent content in recovery concrete to improve the mechanical strength and stability of the fresh mixture. The slump flow test reached a spread diameter of 600 mm, according to brazilian standard NBR 15823-2: 2010 [18].

Specimens were molded according to brazilian standard NBR 5738: 2003 [19], compacted by immersion vibrator and cured immersed in water for 28 days. Seeking to reproduce a structural reinforcement situation by increasing the section of structural member, recovery concrete was a self-compacting concrete, since the casting conditions of concrete in recovery structures, often hinder the compaction. For recovery concrete, w/c ratio was lower than that for substrate concrete, in order to promote high durability, delaying possible structural deterioration.

Analysis of variance (ANOVA one factor) was used to compare the bond strength in relation to surface treatments used.

2.1 Bond Strength tests by tensile stress under diametric compression

For substrate concrete, ten specimens were casted in cylindrical molds with 100 mm diameter and 200 mm height, compacted by immersion vibrator and cured by water immersion. At 28 days age, the specimens were broken by tensile stress under diametric compressive load (indirect tensile test). The average value of this tensile strength was taken as comparison parameter with the result to be obtained for bond between the old and new concrete under same test conditions. From 20 halves of specimens, 12 of them were chosen, which were let at environment of the Laboratory, for six months for aging.

The halves of specimens were put into cylindrical molds and then these were complemented with the recovery of concrete. The rupture surfaces of the halves of substrate concrete specimens received one of three types of treatments, before casting of recovery concrete, as described below.

- Only brushing the surface with brush with steel bristles
- Brushing and application of layer about 1 cm of mortar with the same proportions of the substrate concrete
- Surface brushing and epoxy adhesive application

For each type of surface treatment, four specimens were molded. After mold removal, with 24 hours, the specimens with substrate and recovery concretes were kept in water for 28 days. After this time, tensile tests were performed by diametrical compression, so as to request the interface between old and new concrete. Thus, the bond strength at the interface was obtained. Obtained values were compared with the strength of concrete substrate under same stress condition.

Bond strength values were obtained from diametrical compressive rupture load by Equation 1.

$$\tau_b = \frac{2P}{\pi . d . l_i} \quad (1)$$

Where:
P is the load at rupture of the specimen;
d is the specimen diameter;
l_i is the specimen length.

2.2 Bond Strength test by oblique shear

For these tests, 12 prismatic specimens were produced with substrate concrete and recovery concrete, as shown in Figure [1]. Each specimen measured 100 mm x 100 mm x 300 mm. First, substrate concrete was applied up to one half of the mold, where there was a separator plate. After being demolded and cured for 28 days by immersion in water, the halves of specimens with concrete substrate were undergone a process of natural aging in the laboratory environment for 90 days. After that, these specimens

Figure 1 – Scheme of the specimens for bond strength test by shear oblique

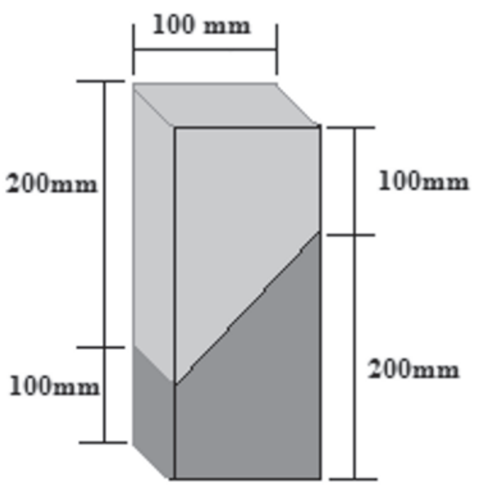


Figure 2 – Mold complemented with concrete substrate

received the specified treatment at the interface between the two types of concrete. Thus, four specimens were produced for each series, with its respective type of treatment, among those already used in tensile tests by diametrical compression (Item 2.1). After applying the treatments, aged samples were replaced in the molds and these were supplemented with recovery concrete as shown in Figure [2]. After curing by immersion for 28 days, the samples were submitted to axial compressive test to cause oblique shear stress, measuring the bond strength between new concrete and old concrete.
The bond stress at rupture by oblique shear was obtained by Equation 2.

$$\tau_b = \frac{P.(\cos 45^\circ).(\mathrm{sen} 45^\circ)}{l_i^2} \quad (2)$$

Where:
P is the load at rupture of specimen;
li is the side length of transversal section of specimen.

2.3 Bond strength test by vertical shear

Nine specimens were produced, with the front shape and dimensions shown in the scheme of Figure [3] and with 180 mm length. First, the central part of specimens was molded. These elements were demolded after 24 h and were cured immersed in water for 28 days. After that, the specimens, still incomplete, were divided into three groups with three specimens, which later received the specified treatment at the interface and, then, the recovery concrete, as described in item 2.1.
These incomplete specimens were subjected to aging in the laboratory for 90 days. After aging, the samples were replaced in the molds and complemented with recovery concrete, on both sides of the mold, after specific treatment for the interface between the two types of concrete, according to each group of specimens. The samples were submitted to axial compressive test.
Results of bond strength through vertical shear stress were obtained by Equation 3.

$$\tau_b = \frac{P}{2.b.h} \quad (3)$$

Where:
P is the load at rupture of specimen;
b is the horizontal dimension of the contact surface between the concretes;
h is the vertical dimension of the contact surface between the concretes.

2.4 Pull out test of steel bars inserted in concrete

Pull out tests were carried out to determine the steel-concrete bon strength, simulating the replacement situation or addition of steel bar in reinforced concrete structures. Eight prismatic specimens of substrate concrete were produced, with dimensions of 100 mm x 100 mm x 200 mm. Four of them were produced with a steel bar segment of eight millimeters (5/16") in diameter, already inserted during casting, with inserted length of 80 mm, i.e., ten times the nominal diameter of the bar. The other four specimens were kept without steel bar inserted, from curing until the end of the aging period. These specimens were cured envolved in airtight plastic bags for 28 days. After the curing period, the samples were left to air in the laboratory for 90 days. Then the specimens that did not contain inserted bars were drilled with a drill with diameter of 10 mm and the holes were filled with epoxy resin as a bridge for bond between steel and concrete. Immediately, the steel rod segments were inserted and their diameters had the same dimensions as those that were used in the four specimens already molded with bar segment inserted.
Both the bar segments placed during casting, for the inputted with epoxy-based adhesive, had 80 mm length inserted in the concrete,

Figure 3 – Scheme of the specimens for bond strength test by vertical shear

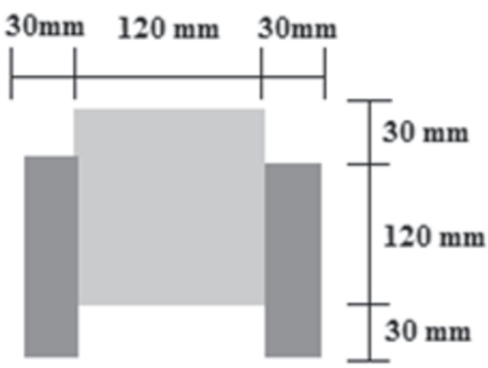
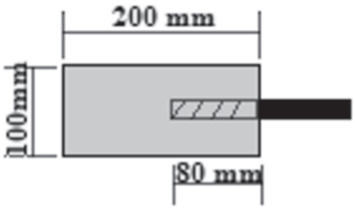


Figure 4 – Scheme of specimen for pull out test



as shown in Figure [4]. This steel bar inserted length value was established in this study based on study of Zhu et al. [20], which carried out pull out tests to determine the bond strength between steel bar and concrete, according to the recommendation of RILEM TC 9-RC [21], in that each specimen was reinforced with steel bar with 12 mm or 20 mm in diameter and utilized the anchorage length of 120 mm for all steel bars. For the 12 mm diameter bars, the anchoring length corresponds to 10 times the bar diameter. Furthermore, the brazilian standard NBR 6118: 2014 [16] recommends that in intermediate supports, the anchoring length should be equal to 10 times the diameter of the bar in the absence of positive moment in the region.

Figure 5 – Apparatus for pull out test

The specimens were submitted to tensile test to pull out the steel bar segment inserted in concrete. An apparatus was fitted to pull out test, comprising a support for the concrete specimen. This apparatus had a smooth steel bar welded to its top, so that, in the claw of the tensile testing equipment, the smooth steel bar was fixed superiorly, the flat bar welded to the apparatus, and inferiorly, the steel bar segment inserted in concrete was pulled out, as shown in Figure [5]. From the pullout loads that broke the bonds between steel bar and concrete, the bond strength (fb) was calculated by Equation 4.

$$f_b = \frac{P}{\pi . d . l_i} \quad (4)$$

Where:
P is the load that pulls out the steel bar;
d is the diameter of the steel bar;
l_i is the length of steel bar inserted in the concrete specimen.

3. Results and discussion

3.1 Tensile strength by diametrical compression of substrate concrete

The cylindrical specimens molded only with substrate concrete were tested in tensile test for diametrical compression and the measurements values were used as a reference for analyzing the performance of the connection between the original concrete and the recovery concrete when subjected to this stress condition. Ten specimens were tested resulting in the average value of 2.88 MPa, with standard deviation of 0.45. As the substrate concrete has a characteristic compressive strength (f_{ck}) of 30 MPa, the average value obtained in the tensile test by diametrical compression is next of expected. According to Mehta & Monteiro [1], the relationship between the tensile strength values and the compressive strength of concrete is around 7% to 10%.

3.2 Bond strength between substrate concrete and recovery concrete under traction by diametrical compression

The results obtained for the bond strength by tensile stress by diametrical compression are shown in Table [2]. Regarding the interface between the substrate and the recovery concrete that received only brushing, the results showed that there was a 15% increase in bond when applied, besides brushing, a thin layer of mortar on the contact surface between concretes. When comparing the average values of the specimens submitted only to brushing with those submitted to brushing and applying epoxy layer, there was a 37% increase in bond strength for the specimens with bonding bridge of epoxy.

Table 2 – Results of bond strength of tensile by diametrical compression

Treatment method	Bond strength parameters	
	Average (MPa)	Coef. of variation (%)
Brushing	1.94	8.99
Brushing-mortar	2.23	9.00
Brushing- epoxy	2.66	19.49

Comparing the average diametrical compression tensile strength of the substrate concrete, which was 2.88 MPa, the average value obtained for bond strength by the indirect tensile test of specimens composed of substrate concrete and recovery concrete, only with brushing, there was a reduction of about 33% in tensile strength by diametrical compression. This reduction was 23% for specimens receiving brushing and mortar layer, and 8% for specimens receiving brushing and epoxy layer. This leads to the conclusion that under tensile stress by diametrical compression, the bond between the substrate concrete and recovery concrete does not reach the level of strength for monolithic specimens, in spite of using the bonding bridge with epoxy adhesive. According to analysis of variance, there was no significant difference between the values obtained (ANOVA, $F = 3.49$; $F_{crit} = 5.14$; $p = 0.10$).
It is possible to notice the failure mode at the interface between the substrate concrete and recovery concrete by direct observation of where the break of the specimens happened. In specimens which only brushing was performed, it was observed that the breakage of the connection occurred both at the interface between the two concretes, as in some regions in substrate concrete, as shown in Figure [6]. In specimens that received brushing and mortar layer, the rupture occurred in the mortar of the binding layer, as shown in Figure [7]. Remaining adhered parts of mortar were observed on the concrete substrate and another parts attached to the recovery concrete.
In specimens that received brushing and epoxy bonding bridge, preferential fracture between the epoxy resin and the recovery concrete was observed, as shown in Figure [8], indicating a greater adherence between the epoxy resin and the substrate concrete, which had higher w/c ratio that the recovery concrete, therefore more porous.

Figure 6 – Specimens after bond test of tensile by diametrical compression with just a brushing

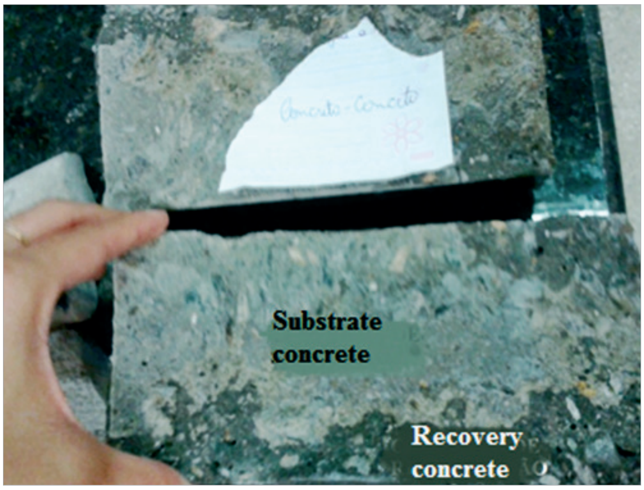


Figure 7 – Specimens after bond strength test of tensile by diametrical compression with brushing and mortar layer

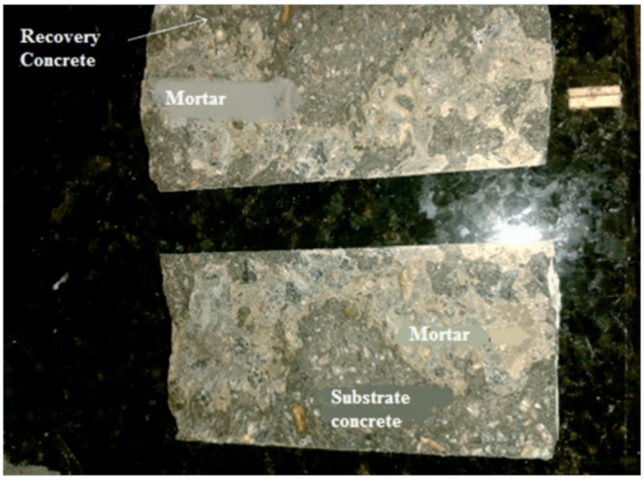


Figure 8 – Specimens after bond strength test of tensile by diametrical compression with brushing and epoxy layer

Table 3 – Results of bond strength test by oblique shear

Treatment method	Bond strength parameters	
	Average (MPa)	Coef. of variation (%)
Brushing	20.88	17.83
Brushing-mortar	21.71	14.07
Brushing- epoxy	23.38	8.07

Table 4 – Results of bond strength test by vertical shear

Treatment method	Bond strength parameters	
	Average (MPa)	Coef. of variation (%)
Brushing	1.43	6.68
Brushing-mortar	2.97	4.58
Brushing- epoxy	3.97	25.48

3.3 Bond strength by oblique shear between substrate concrete and recovery concrete

The results for the bond strength by oblique shear tests are shown in Table [3]. In relation to the interface between substrate and recovery concretes that received only brushing, the average bond strength value of the samples, which received brushing and intermediate layer of mortar, was 4% higher. For the samples with epoxy bonding bridge, the average bond strength was 12% higher. According to the analysis of variance there was no significant difference between the values obtained (ANOVA, F = 0.75; Fcrit = 4.74; p = 0.51). It was noted that specimens with any of interfacial treatment type showed a disintegration in part of the substrate concrete, but the fracture was initiated and propagated at the interface between the two concretes, as shown in Figure [9].

3.4 Bond strength by vertical shear between substrate concrete and recovery concrete

Table [4] shows the values obtained in bond strength test by vertical shear. Comparing the bond performance by vertical shear between substrate concrete and recovery concrete, it was observed that for specimens with mortar as interfacial layer, the bond strength was more than twice the bond strength of specimens that received only brushing at the interface, with increase of 108%. For the specimens receiving epoxy layer at the interface, this increase in bond strength was 178%. According to the variance analysis, there was significant difference between the values (ANOVA, F = 15.30; Fcrit = 6.94; p = 0.01).

It can be seen that fracture occurred in both contact faces between concretes, as shown in Figure [10]. Specimens, that received brushing and mortar interfacial layer, broke, preferably, at the mortar layer. In specimens that receiving brushing and bonding bridge of epoxy, it was noted that the epoxy layer remained adhered to substrate concrete, probably due to the same reason mentioned in item 3.2.

Figure 9 – Specimens tested at bond strength by oblique shear

Figure 10 – Specimen after bond strength test by vertical shear

3.5 Comparison of bond strength test methods

Comparing the test methods (tensile by diametrical compression, vertical shear and oblique shear), it was realized that the latter showed higher bond strength average value than those obtained in the other test types. While the values obtained in bond strength test by indirect tensile and vertical shear ranged from 2 to 4 MPa, those obtained in the oblique shear test were in the range of 21 to 23 MPa. Such discrepancy between the results of bond strength tests should be mainly due to stress states that predominated in specimens. It could be explained by the fact that the predominant stress states, in this test type, is a combination of compressive stress and shear stress. Compressive stress is the more favorable condition for concrete.
Variations between the results of testing, on specimens with different interfacial treatments for the same type of test, were noted as quite important. While for oblique shear bond test there was an increase in bond strength, between specimens with epoxy resin treatment and specimens only with brushing, of 12%, for bond test by vertical shear, that increase was 178%. Thus, it can be stated that, for different test types, the importance of the treatment applied to the interface between the concretes is variable. That is, for the bond strength test by vertical shear, the effect of the interfacial treatment showed more important than for other test types.

3.6 Bond strength between steel and concrete

Results of pull out tests of steel bar inserted in concrete are shown in Table [5]. It was noted no significant difference for steel-concrete bond strength for the steel bar inserted into the still fresh concrete or inserted into concrete after 90 days age. Although specific conditions of this study should be considered, test results may suggest that the anchoring steel bars at recovering structures, using epoxy resin bonding, can be approximate in performance of steel bar originally inserted in concrete.
After testing, it was noted that the specimens that did not receive bonding bridge with epoxy resin had fragmented concrete, while those who received that bonding bridge showed cracks that have spread from the bar insertion point in the concrete, as shown in Figure [11]. It can be assumed that the steel that was inserted into the still fresh concrete, when steel bar is pulled out, the concrete surrounding the steel bar is punched, creating a tensile stress state to be supported by concrete. The insertion of steel bar with bonding bridge of epoxy promotes reduction of damage caused by pull out of steel bar, because this polymer is endowed with higher tensile strength than that of concrete.

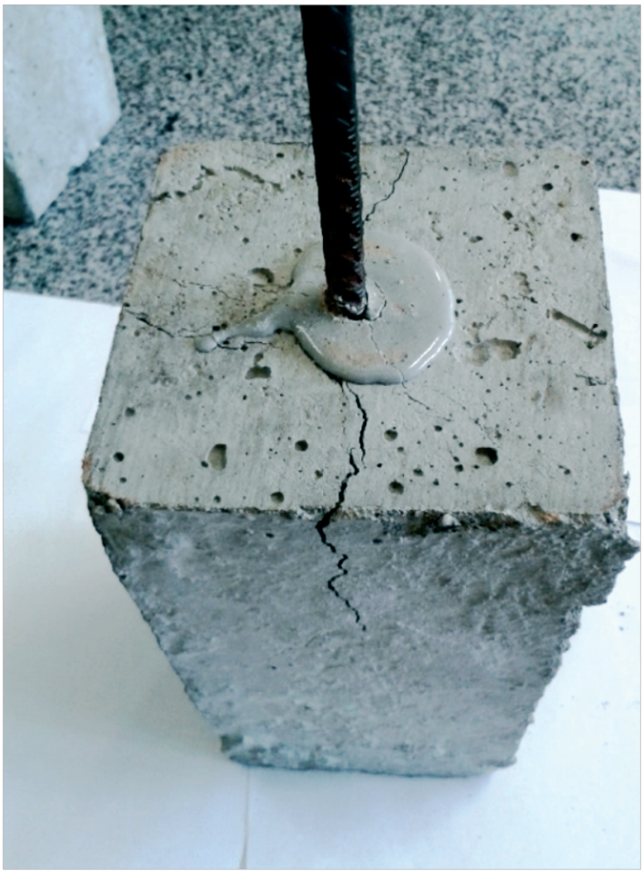
Table 5 – Results of bond strength test between steel and concrete

Bond condition	Bond strength parameters	
	Average (MPa)	Coef. of variation (%)
Steel bar inserted during casting	13.47	16.8
Steel bar inserted by drilling and epoxy	13.40	12.5

4. Conclusions

Results from bond strength test in tensile by diametrical compression showed that even with the use of interfacial treatments between substrate concrete and recovery, the bond between these two concretes is not equal to indirect tensile strength value of the monolithic element, composed of single concrete. Comparing the bond strength between substrate and recovery concretes and the tensile strength by diametrical compression of specimens with substrate concrete, it was observed a reduction in strength of about 8% even when interfacial treatment was applied with brushing and subsequent bonding bridge of epoxy.
Comparing the results from bond strength tests of traction by diametrical compression between substrate and recovery concretes, it was noticed that there was a 15% increase in bond strength, when in addition to simply brushing, a layer of mortar was applied at the interface between the concretes. When the treatment consisted of brushing and a epoxy bonding bridge, this increase was 37%, compared to bond strength at interface between concretes that was simply brushed.
Bond strength tests by oblique shear between substrate and recovery concrete showed a minor variation for the three types of interfacial treatment applied. Specimens that received brushing

Figure 11 – Specimen with epoxy bonding bridge after pull out test



and mortar layer had an average bond strength value only 4% superior, compared to those who received only a brushing at interface. Specimens that received, in addition to brushing, the epoxy interfacial layer had increased the average bond strength value of about 12% compared to those who received only brushing.

For bond strength tests by vertical shear, the results showed a highly significant variation between the average values of the bond strength between the two types of concrete for the different treatments at the interface. This increase reached 178% among the specimens receiving epoxy layer at the interface and those that receiving only a brushing. Among those who received mortar layer and those who received only brushing, the increase was 108%.

Momayez et al. [17] stated that, among the bond strength tests for concretes, which showed the highest reliability, based on coefficients of variation, was the oblique shear. However, when assessing the means values of bond strength tests between concretes for the three types of tests performed, it was realized that bond tests by oblique shear showed the highest average values for this property, in a range between 20 and 24 MPa. For bond strength tests by indirect traction and vertical shear, average bond strength values were in the same order of magnitude ranging between 1.5 and 4.0 MPa.

In this study, the results showed that the bond strength test by indirect tensile and by vertical shear caused stress states in specimens that requested more intensely the interface between the substrate concrete and recovery concrete. It can be assumed that the greatest bond strength averages observed in the oblique shear tests were a result of the stress state to which the specimens were subjected during the test, with a prevalence of compressive stresses in the concrete. As compressive stress is the best condition for concrete, it can be concluded that this factor had a great influence in determining values for the resistance in this test type.

The analysis of bond strength between concrete and steel showed irrelevant difference in the interface bond strength between the two materials, both when the steel was inserted in the fresh concrete, as when the steel was inserted by drilling in the hardened concrete, with bonding bridge of epoxy. This shows the great adhesiveness of epoxy, in relation to the concrete and steel.

It was possible to conclude that the interfacial treatment that presented the best results in bond strength between the substrate concrete and recovery concrete, among the three types studied treatment was brushing the surface and then applying epoxy bonding bridge. This treatment can be taken as the best alternative for repair or reinforcement of concrete structures, among the studied treatments, surpassing in up to 178% as compared to simply brushing, as showed in results of vertical shear test.

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