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Bond Behavior between Recycled Concrete Containing CDW and Different Types of Steel Bars

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ABSTRACT

The operation of reinforced concrete structures is directly associated with the adhesion between the steel bar and the concrete, which allows the internal forces to be transferred to the reinforcement during the process of loading the structural elements. The modification of the concrete composition, with the introduction of recycled aggregate from construction and demolition waste (CDW), affects the steel-concrete interface and can modify the bonding stress, which is also influenced by the type and diameter of the bar used. In this work, the influence of the recycled fine aggregate (RFA) and types of steel bar on the steel-concrete bond was experimentally evaluated using the pullout test. Conventional concrete and recycled concrete, with RFA replacement level of 25%, were produced. Two types of steel rebars (i.e., plain and deformed) with diameters of 10.0 and 16.0 mm were considered in this paper. The results indicate a reduction in the adhesion stress with the introduction of recycled aggregate, but this trend is influenced by the diameter of the bar used. The use of ribbed bars modifies the stress bond-slip behavior, with an increase in the average bond strength, which is also observed with the reduction of the diameter of the bar.

1. Introduction

The use of construction and demolition waste for the production of concrete and mortar, as a substitute for natural aggregates, is an important alternative for reducing the environmental impact of the civil construction sector. The application of this type of recycled aggregate, replacing the fine and coarse natural aggregate, in the production of reinforced concrete structural elements, has been successfully evaluated by several researchers around the world^[1-4] which will allow the expansion of the reinsertion of this waste in the sector productive.

However, due to the differential characteristics of re-

cycled aggregates, in relation to the natural aggregate, its use in larger quantities can result in a significant reduction of the compressive strength and tensile strength^[5] and the fracture mode of the concrete^[6]. Due to this, the recycled fine aggregates have been banned or have limited substitution content by some reinforced concrete design standards to be used in structural concrete^[7].

The reduction in mechanical properties directly affects the steel-concrete bond and the structural behavior of reinforced concrete elements produced with recycled concrete. According to Mukai et al^[8], the use of recycled aggregate can affect the behavior of reinforced concrete beams when the recycled aggregate is used to replace

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the natural aggregate; the authors found a reduction in the shear strength and crack load of the beams, when compared with the conventional concrete beam, which was attributed to the lower adhesion between steel and recycled concrete. Other studies on the effect of recycled aggregate on steel-concrete bond have been developed but have not shown a consensus between the results. While some researchers did not verify any influence of the recycled aggregate on the bond-slip behavior^[9, 10], in another study a reduction in the bond stress was verified with the substitution of the natural aggregate by the recycled aggregate^[11]. This apparent contradiction is associated with the characteristics of each work, since several parameters affect the steel-concrete bond behavior, such as composition and type of recycled aggregate, type of steel and diameter of the bar and also the mechanical properties of the concrete.

Thus, in order to allow the application of recycled aggregate in reinforced concrete safely, it is necessary to assess how the parameters associated with the bonding stress, such as bar diameter and bar texture, affect the stress-slip behavior in concrete with recycled aggregate.

The objective of this work is to verify the effect of the addition of recycled fine aggregate and the characteristics of the steel bar on the bond stress-slip behavior. Pullout test was performed to determine the adhesion between concretes with 25% recycled fine aggregate and steel bars. Four types of steel bars were evaluated, with 10 mm and 16 mm diameters and with plain or deformed surface texture.

2. Materials and Methods

2.1 Materials

Two natural fine aggregates used were: fine river quartz sand (NFA1) and medium (NFA2) river quartz sand. The granitic aggregate, with specific gravity of 2.69 kg/dm³ and maximum size aggregate of 9.5 mm, was used as natural coarse aggregate (NCA). The aggregate properties are presented in Table 1. As a binder, the Portland cement (C) composed with pozzolan (type CP II Z - 32), with a specific mass of 2.89 kg/dm³, was used. Drinking water was used in all mixtures.

The recycled fine aggregate (RFA) was obtained from the grinding, in a jaw crusher, of demolition waste composed of mortar, ceramics and concrete, in the proportions of 29%, 27% and 44%, respectively. After grinding, the residue was sieved through a 4.8 mm sieve and characterized, as shown in Table 1.

Table 1. Physical properties and granulometric analysis of aggregates

Properties (test method)	Fine aggregates			
	NFA1	NFA2	RFA	
Granulometric analysis	Sieve opening (mm)	%passing		
	4.8	99	100	100
	2.4	99	85	85
	1.2	98	52	72
	0.6	87	37	52
	0.3	33	24	30
	0.15	7	21	16
Maximum size aggregate (mm) (NBR NM 248/03)	1.2	4.8	2.4	
Fineness (NBR NM 248/03)	1.77	3.47	2.46	
Specific gravity (kg/dm ³)	2.61	2.57	2.18	
Bulk density (kg/dm ³) (NBR 7251/82)	1.60	1.46	1.37	
Water absorption rate (%)	0.1 ¹	0.2 ¹	18.8 ²	
Fines content (%) (NBR NM 46/03)	2.1	0.8	10.0	

¹ Experimental Method: NBR NM 30/03; ² Experimental Method: Leite^[10]

For this investigation, deformed and smooth steel bars with diameters of 10 mm and 16 mm were used. The yield strength of the bars was determined according to NBR ISO 6892^[12] and a value of 800 MPa was obtained.

As shown in Table 2, two mixes were prepared with natural aggregate (REF) and with fine recycled aggregate (25% CDW) replacing the 25%, in volume, of fine natural aggregate. As can be seen in Table 1, the water absorption of the recycled aggregate is around 18%. Because of this, the addition of recycled material in the mixture tends to absorb part of the water used and reduce the workability of the concrete in the fresh state. As a result, there is a difficulty in launching the concrete. In this way, an additional amount of water, called "compensating water", was inserted into the mixtures, to compensate for the aggregate water absorption rate and not to reduce the workability of the concrete in the fresh state. However, to avoid an increase in the water/cement ratio and a possible reduction in mechanical strength, the amount of free water was corrected, considering a water absorption from the recycled aggregate for a time of 10 minutes. This mixing time was then adopted for all concretes. The proportions of the mixture for all lots are detailed in Table 2. A scientific method of mix design, based on the compressible packaging method, was used to provide mixtures, and is presented in detail in^[13].

Table 2. Composition of concrete

Mix	%CDW	Mix proportions (kg/m ³)								Slump (mm)
		C	NCA	NFA1	NFA2	RFA	water	compensating water	water total	
REF	0	360	892.8	604.8	259.2	-	212.4	0	212.4	100
25%CDW	25	360	892.8	453.6	194.4	198.0	212.4	28.8	241.2	115

2.2 Preparation of Pull-out Test Specimens

Figure 1a shows a schematic drawing with the dimensions of the pull-out specimens and positioning of the steel bars. It can be seen in Figure 1b that the production process was carried out with PVC molds supported on wooden structures and with vertical positioning of the bars. The relationship between the diameter of the steel bar and the diameter of the concrete cylinder was kept equal to 10. A portable needle vibrator was used to consolidate the fresh concrete in the samples (Figure 1c).

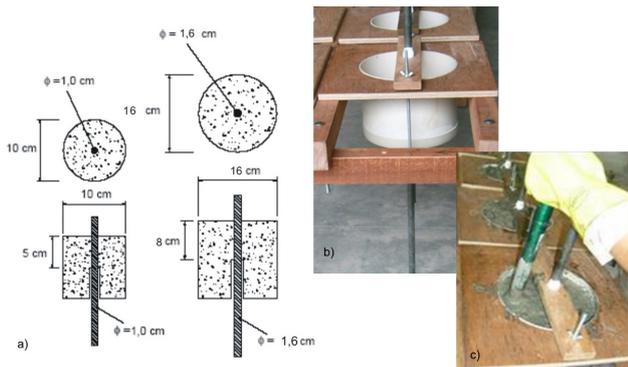
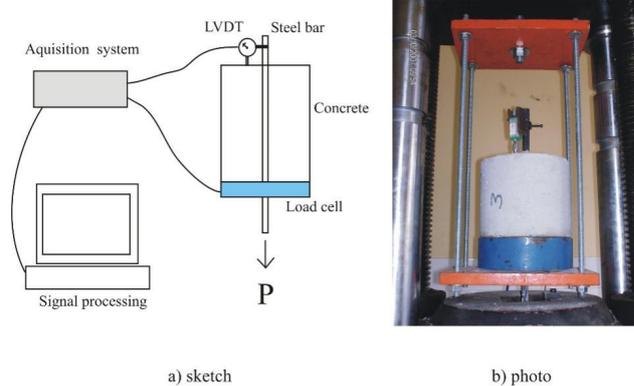


Figure 1. Pull-out specimens production: a) dimensions; b) PVC molds; c) casting and vibrator.

2.3 Test Procedures

The pullout test was carried out according to the RILEM standard [14] and is shown in Figure 2. To assist in the test, a metallic apparatus consisting of two steel plates with central holes, 30 mm thick and connected with four bars threaded was manufactured. The upper plate of the apparatus was connected to the clamp of the test machine and the specimen was positioned inside it. The steel bar of the sample was then attached to the machine's claw at the bottom and subjected to a tensile load. The sliding of the bar was measured by a linear variable differential transformer (LVDT) attached to the upper part of the specimen and the load was measured by a load cell, with a capacity of 300 kN and positioned under the sample, as shown in Figure 2b. An automatic signal acquisition system was used to capture the load and displacement values in real time that allowed obtaining the load-slip curve. A 1000 kN universal test ma-

chine with load control was used.



a) sketch b) photo

Figure 2. Pullout test setup

To determine the mechanical properties of concretes, axial compression and splitting were carried out in cylindrical samples with 100 mm in diameter and 200 mm in height after 28 days of curing in a humid environment (95% RH). The specimens were tested on a 2000 kN testing machine.

3. Results and Discussion

3.1 Mechanical Properties of Concrete

Table 3 shows the experimental results of mechanical tests.

Table 3. Compressive strength (f_c), splitting strength (f_{td}) and elastic modulus (E_c) of reference and experimental concrete sample

Mixture	%CDW	f_c (MPa)	f_{td} (MPa)	E_c (GPa)
Referência	0	23.65 ± 1.06	2.08 ± 0.04	30.50 ± 0.43
25%CDW	25	22.82 ± 0.58	1.70 ± 0.09	25.58 ± 1.71

It can be seen in Table 3 that the addition of recycled aggregate as substitution to the natural aggregate resulted in a reduction of 3.5%, 18.3% and 16.1% in compressive strength, splitting strength and elastic modulus, respectively.

The reduction in mechanical properties with the introduction of recycled aggregates has been observed by other researchers [15-17] and may be associated with an

increase in the water content of the mixture, the greater fragility of the recycled aggregate grain, when compared to the natural aggregate or due the saturation level of the recycled aggregates may affect the strength of the concretes.

3.2 Bond Stress

The experimental stress bond versus slip curves of pull-out test with 10 mm and the 16 mm diameter bars are presented in Figure 3.

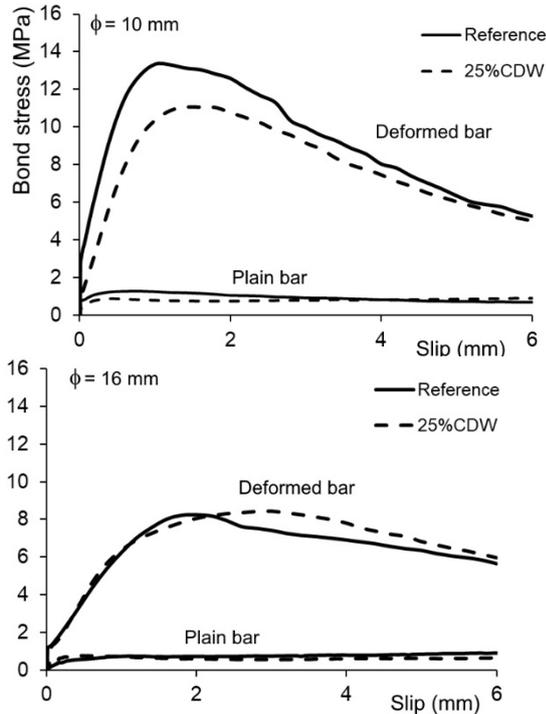


Figure 3. Experimental bond stress-slip curves

The steel-concrete bond is formed by the combination of three components associated with chemical adhesion, mechanical anchoring and friction. When using smooth bars, chemical adhesion is the predominant mechanism, and the adhesion stress is usually weak. In the pullout test with smooth bars, after the rupture of the chemical adhesion, the increase in loading generates the longitudinal cracking of the steel-concrete interface along the bar. Subsequently, a pullout process characterized by an increase in sliding and maintenance of a practically constant load, as schematically shown in Figure 4. This phenomenon was also observed in the experimental results obtained with smooth bars shown in Figure 3.

In the corrugated bars, on the other hand, the ribs provide a mechanical lock that allows the development of greater bond stress after overcoming the chemical adhesion. The mechanical interlock, which is generated by the ribs of the bar and the concrete, provides bearing

force against the face of the bar ribs, as shown in Figure 6. The cracking process at the steel-concrete interface is then characterized by an increase in the adherence stress to a maximum stress level, after which the complete rupture of the interface and the reduction of bond stress can be observed in a process called shearing off (Figure 4).

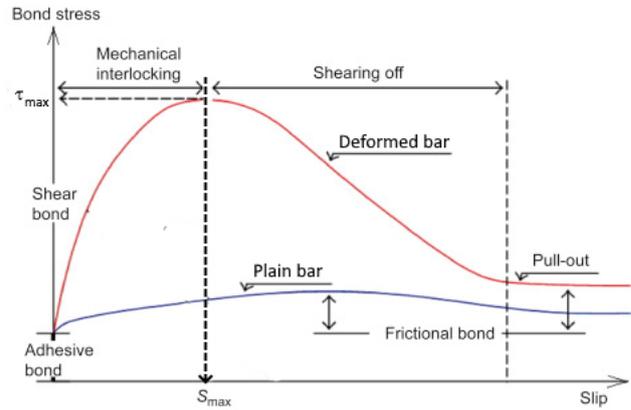


Figure 4. Schematic bond stress-slip relationship [18]

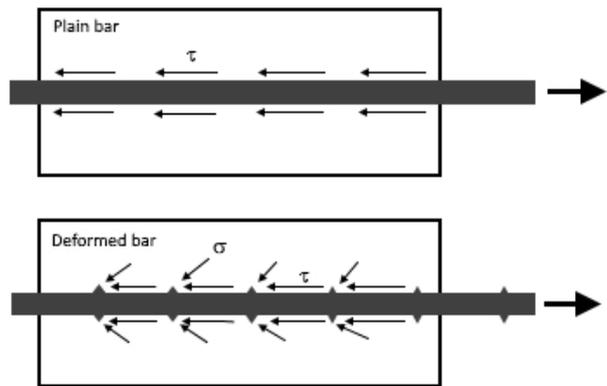


Figure 5. Local bond response on plain and deformed bar (adapted from [19])

Considering the theoretical model shown in Figure 5 [19], the bond stress in the pullout test can be considered constant along the length of the steel bar embedded in the concrete. Thus, the bond stress τ is given by:

$$\tau = \frac{P}{\pi\phi l_b} \tag{1}$$

where P is the load; l_b is the embedded length of the steel rebar and ϕ is the diameter of the steel rebar.

The average bond strength τ_m is obtained by media of three bond stresses relatives to slip of 0.01 mm ($\tau_{0.01}$), 0.1 mm ($\tau_{0.1}$) e 1.0 mm ($\tau_{1.0}$):

$$\tau = \frac{\tau_{0.01} + \tau_{0.1} + \tau_{1.0}}{3} \tag{2}$$

From Equation (1) it is possible to obtain the maximum

bond strength, τ_{max} , using the maximum load obtained in the test. However, when the maximum load is obtained for a displacement below 1 mm, the value of $\tau_{1.0}$ is adopted as the maximum stress.

Table 4 shows the experimental results of pull-out test.

It can be seen that, when using plain bars, the average bond strength is usually lower, reaching maximum values in the order of 0.98 MPa, as shown in Table 4. For the deformed bars, average bond strength varied from 2.76 MPa to 6.89 MPa, which represents an increase of up to 9 times in the adhesion when compared with the plain bar, due to the mechanical anchoring effect provided by the ribs.

In addition to the surface texture, it is verified in this work that the diameter of the bar affects the development of bond stresses. The results shown in Table 4 indicate that the average bond stress, τ , decreases with the increase in the bar diameter. For conventional concretes, this reduction is about 62% when the diameter of the bars varies from 10 mm to 16 mm. For recycled concrete, the reduction in the average bonding stress, τ , with the increase in the bar diameter was 45% for plain bars and 38% for deformed bars. The reduction of the bonding stress with the increase in the diameter of the bars was observed by [20] for conventional reinforced concrete with bars of 12, 16 and 20 mm. According to [16, 17] this phenomenon is associated with the steel-concrete interface; in the 16 mm bars the thickness of the transition zone is greater than in the 10 mm bars, which facilitates the trapping of air and water close to the rib and, consequently, reduces the adhesion of the bar with the concrete. The reduction in mean porous zone thickness can be considered one of the many influencing factors that resulted in increased ultimate bond strength [21]. During the concrete casting

process, voids can form under the bars or close to the ribs, generating a bleed water zone [22] that affects the steel-concrete adhesion and even the durability of the bar.

Regarding the use of recycled aggregate, there is a tendency to reduce the average bonding stress, which is mainly influenced by the reduction in the tensile strength of recycled concrete, when compared to conventional concrete, as shown in Table 3. This behavior was identified by Choi and Kang [9] and which verified that the bond strength decreased with the increasing recycled aggregate ratio. However, the bar diameter differently affects the adhesion ratio between steel and recycled concrete. While for deformed bars with 10 mm there is a reduction of about 35% of the average bond stress with the introduction of recycled aggregate, in the test with deformed bars of 16 mm, the introduction of recycled aggregate resulted in an increase of 16% in this bond strength, demonstrating that there is an interaction between these two parameters. For plain bars, the adhesion between the bar and recycled concrete decreased by 39% and 11%, for bars of 10 mm and 16 mm, respectively. The combined effects of recycled aggregate addition, type and diameter of steel the bond strength have shown no clear tendency in the current study. Xiao and Falkner [9] also verified the interaction between the use of recycled aggregate and the type of steel bar; the authors found that the bond strength between the recycled aggregate concrete and the plain rebar decreases while the bond strength between the recycled aggregate concrete and the deformed rebar is similar.

4. Conclusions

Based on the experimental results obtained with

Table 4. Results of the pullout test

Mistura	%CDW	ϕ (mm)	Bar type	P_{max} (KN)	$\tau_{0.01}$ (MPa)	$\tau_{0.1}$ (MPa)	$\tau_{1.0}$ (MPa)	τ_{max} (MPa)	τ_m (MPa)
T0P10	0	10	Plain	2.06 ± 0.20	0.72	0.92	1.27	1.31	0.98
T25P10	25			1.37 ± 0.10	0.26	0.62	0.81	0.91	0.60
T0D10	0	10	Deformed	21.48 ± 1.08	2.81	4.54	13.33	13.68	6.89
T25D10	25			18.73 ± 1.37	0.97	2.03	10.36	11.90	4.45
T0P16	0	16	Plain	3.04 ± 0.10	0.09	0.32	0.69	0.76	0.37
T25P16	25			3.14 ± 0.01	0.11	0.20	0.68	0.79	0.33
T0D16	0	16	Deformed	33.83 ± .41	1.06	1.36	5.85	8.42	2.76
T25D16	25			33.24 ± 3.14	1.08	1.45	7.10	8.27	3.21

pullout tests on concretes containing recycled fine aggregate, it was possible to obtain the following conclusions:

- The use of recycled fine aggregate to replace the natural aggregate reduces the mechanical properties of concrete, affecting the splitting tensile strength more significantly, affecting the splitting strength more significantly than the compressive strength or the elastic modulus, when compared with conventional concrete.

- The general shape of the load versus slip curve between recycled aggregate concrete and steel rebars is similar to the one for normal concrete and steel rebars.

- The stress-slip behavior is not affected by the introduction of the recycled aggregate, being similar to the behavior of the test with conventional concrete and according to the results already observed in the literature. The use of deformed bars, on the other hand, changes the stress-slip behavior, when compared to the result obtained for the plain bar, due to the mechanical component of bond stress resulting from the effect of locking the ribs.

- For the deformed bars, average bond strength varied from 2.76 MPa to 6.89 MPa, which represents an increase of up to 9 times in the adhesion when compared with the plain bar, due to the mechanical anchoring effect provided by the ribs.

- The reduction of the bonding stress with the increase in the diameter of the bars.

- The average bond strength between the recycled aggregate concrete and the plain rebar decreases for the RCA replacement percentage of 25% while the bond strength between the recycled aggregate concrete and the deformed rebar is dependent of diameter of bar. For deformed bars with a diameter of 10 mm there is a reduction in bond strength with the introduction of recycled aggregate while for deformed bars with a diameter of 16 mm there is an increase in adhesion.

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