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Bond between steel and concrete made with ceramic waste aggregate

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Luciano Passos[1, 2]
http://orcid.org/0000-0002-1477-1880
Armando Lopes Moreno Júnior[1, 3]
Bruno Fernandes[1, 4]
Carla Neves Costa[1, 5]

[1]Universidade Estadual de Campinas - UNICAMP, Faculdade de Engenharia Civil, Arquitetura e Urbanismo, Departamento de Estruturas, Campinas – São Paulo – Brasil.

E-mails: [2]lupa@fec.unicamp.br, [3]almoreno@fec.unicamp.br, [4]fernandes.brn@gmail.com, [5]carlac@fec.unicamp.br

Abstract

The reduction of natural resources combined with a substantial increase in the generation of solid waste in large urban centers, justifies the search for methods of reusing the construction industry waste. The ceramic industry has a high disposal rate during the manufacturing, transportation and eventual replacement of its products. In this case, research on the reuse of ceramic materials is urgent. A possible solution is the employment of ceramic waste as a coarse aggregate in structural concrete. Therefore, the mechanical properties of this new mix of concrete have to be assessed. This study evaluates the bond strength between steel rebar and concrete with ceramic waste aggregates, by means of the pull-out test method, proposed by RILEM-FIP-CEB (1978). Three concrete mixtures were produced: a mixture without any replacement, and two other mixtures with gradual substitution of natural coarse aggregate by ceramic coarse aggregate (40% and 100% substitution, in volume). Nine cylindrical specimens, three for each of the concrete mixtures, were evaluated in laboratorial conditions. Results concerning bond stress between concrete and steel rebar indicated the feasibility of employing ceramic waste to replace part of the coarse aggregate in structural concrete.

Keywords: ceramic waste, concrete, bond.

1. Introduction

The continuing expansion of the construction industry can result in numerous environmental issues, especially the generation of large quantities of waste, often discarded inappropriately, compromising ecological protected areas and water sources. It is noteworthy that much of this waste can be reused, reducing ecological impacts. According to Campos and Paulon (2015), the ceramic industry – which encompasses products, such as ceramic bricks, coatings and porcelain electrical insulators – has a high disposal rate during the manufacturing, transportation and eventual replacement of merchandise. Therefore, research on the reuse of ceramic materials is urgent. A possible solution is the employment of ceramic waste as a coarse aggregate in structural concrete. Structural elements manufactured with alternative concrete mixtures must meet project parameters that aim, above all, at the safety of buildings. This study evaluates the bond properties of concrete mixtures produced with ceramic waste aggregates and steel bars.

2. Previous studies and research significance

Several studies evaluated the bond between steel rebar and concrete mixtures made with aggregates from construction and demolition waste. Xiao and Falkner (2007) evaluated the bond between steel rebar and recycled concrete aggregates. Kim and Yun (2013) investigated the bond behavior of deformed steel rebar and concrete containing recycled aggregate from demolitions. Baena *et al*. (2016) studied the bond strength between glass fiber rebar and concrete with construction waste aggregate. Siempu and Pancharthi (2017) evaluated the mechanical performance and bond strength between steel rebar and a concrete mixture where fine and natural coarse aggregates were completely replaced by aggregates from construction and demolition waste. Wardeh *et al*. (2017) evaluated the bond between steel rebar and six different mixtures of concrete containing recycled concrete aggregate. In all these studies, the evaluation method of the bond between concrete and reinforcement bars was the pull-out test. Results showed a good bond behavior between the reinforcement bars and concrete mixtures produced with recycled aggregates. It is noteworthy, however, that only a few of the experimental programs described in literature evaluated the bond between steel rebar and concrete with ceramic aggregate. Thus, this study investigates the bond between steel rebar and concrete with ceramic waste aggregate and the feasibility of employing these aggregates in structural concrete.

3. Bond stress: standardization and theoretical model

Several standardized equations describe bond strength. These equations often correlate bond strength to split tensile strength or compressive strength. Bond stress measurements are usually obtained via standardized laboratory tests, such as the pull-out test proposed by RILEM-FIP-CEB (1978).

Some of these are presented below, with the respective references indicated.

EUROCODE 2 (CEN, 2004) suggests Eq. 1 for the calculation of bond stress in conditions of high-bond strength reinforcement bars and φ ≤ 32 mm.

$$f_{bd} = \eta_1 \cdot \eta_2 \cdot f_{ctd} \qquad (1)$$

Where, for ribbed bars, $\eta_1 = 2.25$; in good bond conditions, $\eta_2 = 1.00$; and f_{ctd} is the average split tensile strength of the concrete, experimentally obtained.

It is noteworthy that these bond strength expressions are applicable to concrete mixtures with compressive strength of up to 50 MPa, made with natural aggregates. When it comes to aggregates made from red ceramic waste, construction or demolitions waste, equivalent equations are quite scarce.

Recently, Siempu and Pancharthi (2017), based on pull-out test results, proposed an equation to estimate concrete-to-steel bond strength in cases of total substitution of natural aggregates by recycled construction and demolition aggregates (Eq. 2).

$$\tau_{máx} = \left[k1\left(\frac{\theta}{l}\right) + k2\left(\frac{C}{\theta}\right) + k3\right]\sqrt{f_c} \qquad (2)$$

Where, $K_1 = 6.32$ for natural aggregates and 6.38 for recycled aggregates; $K_2 = 0.26$ for natural aggregates and 0.44 for recycled aggregates; $K_3 = 0.21$ for natural aggregates and 0.50 for recycled aggregates; θ = bar diameter (mm); l = embedment length (mm); f_c = concrete's compressive strength; C = average coverage of concrete over steel rebar (mm).

4. Experimental program

Overview

In this research, bonding between steel rebar and concrete was evaluated through the pull-out test method proposed by RILEM-FIP-CEB (1978). Three different types of concrete with a replacement of 0 (REF), 40% (S40) and 100% (S100) were cast. Three samples of each concrete mixture were used for the pull-out tests, resulting in a total of nine samples. Also, twelve cylindrical specimens (10 cm in diameter and 20 cm in height) were obtained for axial compression, elastic modulus, and indirect tensile strength tests.

Materials and execution of samples

The properties of aggregates tested in this study are shown in Table 1. These properties are evaluated according to Brazilian Standards.

Property	Ceramic waste aggregate	Natural coarse aggregate	Fine aggregate (sand)
Bulk Specific Gravity (g/cm³) – NBR NM 53:2009; 52:2009	1.77	2.89	2.63
Maximum Characteristic Dimension (mm) – NBR NM 248:2003	19	19	4.8
Modulus of Finesses (mm) – NBR NM 248:2003	6.41	6.86	2.4
Unit Weight (g/cm³) – NBR NM 45:2006	0.95	1.62	1.47
Lumps of Clay and Friable Materials (%) – NBR 7218:2010	0	0	0
Sieve (75 μm openings) Pass Through Material Contents (%) – NBR NM 46:2003	-	0.69	2.37
Water Absorption (%) – NBR NM 53; 30:2003	19	1.2	0.15

Table 1
Material properties.

Figure 1 illustrates the particle-size analysis of tested coarse aggregates. The natural coarse aggregate had gravel with diameters between 9.5 and 25 mm. The recycled coarse aggregate was obtained from grinding waste produced by tiles and ceramic block factories in the city of Campinas (SP).

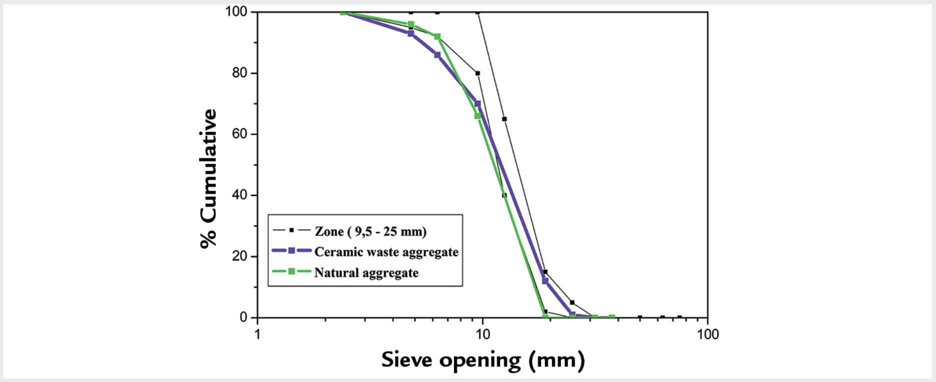


Figure 1
Coarse aggregates particle-size curve.

The cement compound used for the concrete mixtures was CP II E32. It contains up to 10% of blast furnace slag. The used steel had a 529.67 MPa stress at yield point (f_y) and a 0.3% percentage elongation (ε_y) at yield point. Table 2 shows the proportions of materials used in the concrete mixtures. The water-cement ratio was 0.49 for all mixtures and the coarse aggregates are in volume.

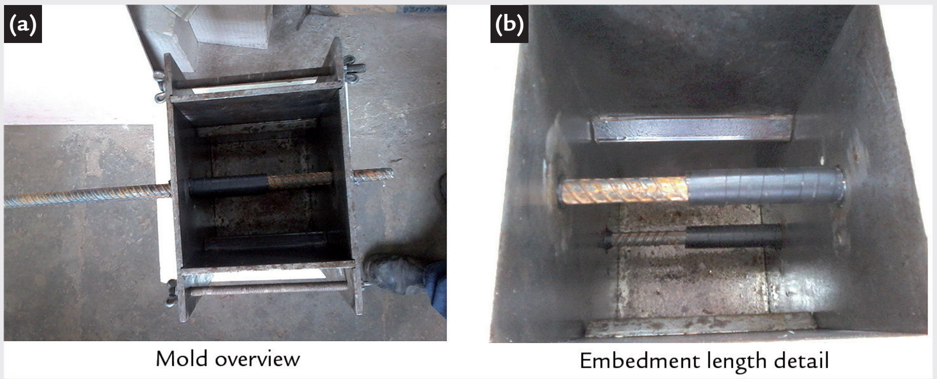
Table 2
Concrete mixtures.

Mix	Cement	Natural fine aggregate	Natural coarse aggregate	Ceramic coarse aggregate	w/c	Slump test (mm)
REF	1	2	1.7	0	0.49	50
S40	1	2	1.0	0.7	0.49	50
S100	1	2	0	1.7	0.49	50

Given the high water absorption of ceramic residue, the aggregates had to be humidified with 80% of their water absorption capacity previous to testing, not being considered this quantity in relation to the water in the cement. This was similar to the procedure executed by Correia *et al.* (2006) and indicated by Brazilian Standard NBR 15116 (ABNT, 2004).

To mold the pull-out specimens, a portion of the rebar had to be isolated with plastic tubing and duct tape, so that only the anchorage length (l_b) was in contact with the concrete (Figure 2).

After casting, specimens were saturated with water and packed in plastic bags, where they remained until the scheduled test date.



Mold overview

Embedment length detail

Figure 2
Cubic form for sample molding.

Test model

Bond tests were done according to the pull-out test method proposed by RILEM-FIP-CEB (1978). The procedure consists of pulling the steel rebar from the concrete prism. The force and the slip between bar and concrete are measured during the test. Eq. 3 is used to quantify bond stress.

$$\tau_b = \frac{P}{\pi . l_b d_{b.}} \text{ (MPa)} \qquad (3)$$

Where: τ_b = bond stress (MPa); P = maximum force applied to the bar (N); d_b = bar diameter (mm); l_b = embedment length (mm).

The embedment length was five times the diameter of the bar (5φ) and the concrete prism had a cubic form with 150 mm sides.

Samples were loaded with a universal testing machine, with a maximum capacity of 1000 kN and precision of 100 N (Figure 3). Loading followed a constant progression, with increments of 100 N per minute, until complete slippage of the steel bar. To measure relative slip, one LVDT was positioned in the rebar extremity.

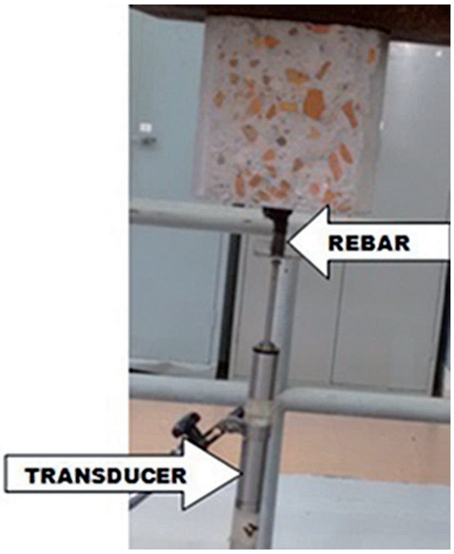


Figure 3
Pull-out test detail, RILEM-FIP-CEB (1978).

Figure 4 shows the bars after completion of the pull-out tests.

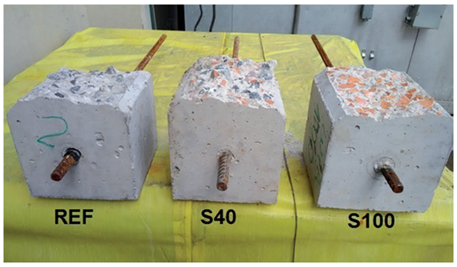


Figure 4
Samples after the pull-out test

5. Results and discussion

Table 3 shows the mechanical properties of each of the concrete mixtures.

MIX	f_{c7} (MPa)	f_{t7} (MPa)	E_{c7} (GPa)	f_{c28} (MPa)	f_{t28} (MPa)	E_{c28} (GPa)
REF	24.26	-	20.00	30.00	3.34	22.10
S40	20.38	2.21	18.05	26.22	2.63	17.45
S100	16.43	2.15	8.0	19.04	2.23	11.30

Where: f_{cj} = compressive strength in *j* days; split tensile strength in *j* days; E_{cj} = concrete elastic modulus in *j* days.

Table 3
Mechanical properties
of analyzed concrete mixtures.

As predicted, the level of substitution of natural aggregate by recycled ceramic aggregate affected the mechanical properties of the concrete mixtures (Table 3). Total replacement of natural coarse aggregate by recycled ceramic aggregate decreased the compressive strength, split tensile strength and elastic modulus by 36.5%, 33.2% and 48.9%, respectively. These values are close to those obtained by SIEMPU AND PANCHARTHI (2017) and KIM AND YUN (2013).

Table 4 shows bond stress (τ_b) results obtained for each of the evaluated samples, calculated according to Equation 3. Also, the average bond stress and maximum bond stress (τ_{br}) for each of the concrete mixtures are shown.

CP	REF		S40		S100	
	Force (N)	τ_b (MPa)	Force (N)	τ_b (MPa)	Force (N)	τ_b (MPa)
01	51300	20.91	40700	16.59	34000	13.86
02	50000	20.38	27000	11.01	17000	6.93
03	27000	11.00	32200	13.13	13200	5.38
Average	42767	17.43	33300	13.57	21400	8.72
Maximum Values	51300	20.91	40700	16.59	34000	13.86

Table 4
Bond stress results
for evaluated concrete mixtures.

Figure 5 presents the bond slip curves for each o the test samples, grouped by concrete mixture.

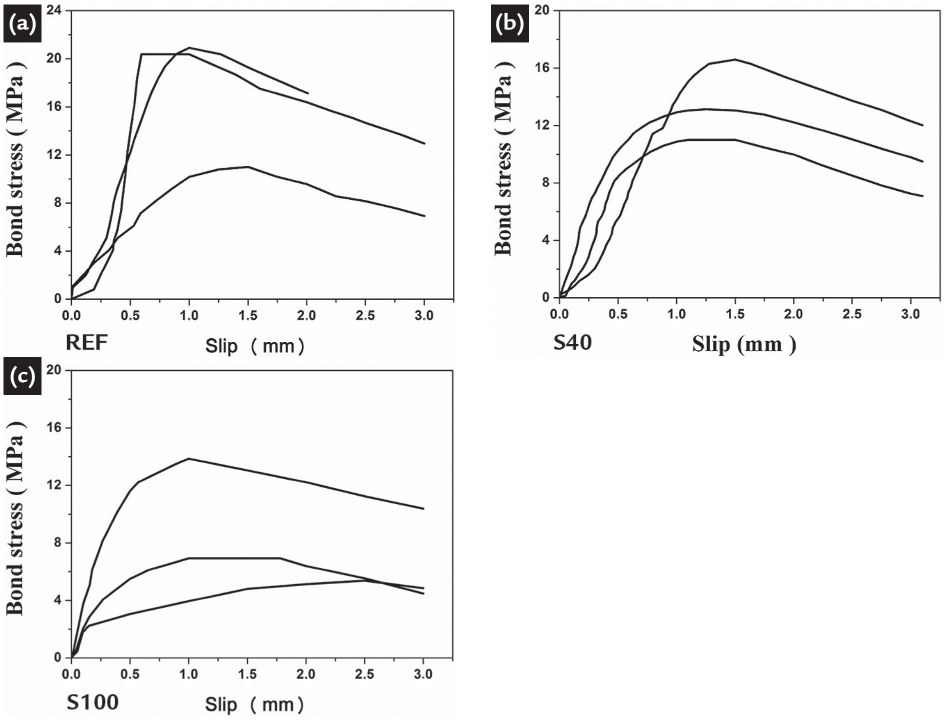


Figure 5
Bond-slip curves for
the evaluated concrete mixtures.

Figure 6 presents the relationship between the average bond stress along with the compressive strength of evaluated concrete mixtures. Baena *et al.* (2016) e Xiao and Falkner (2007) also noted this reduction, associated with the replacement of natural aggregate by recycled aggregate.

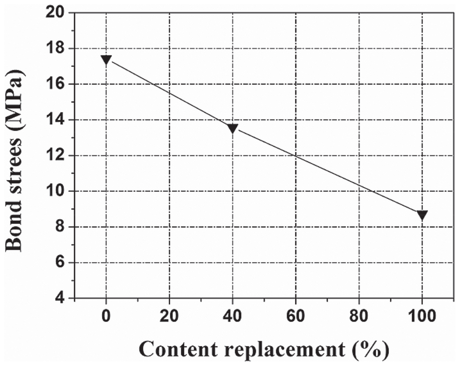


Figure 6
Average bond stress in relation
to contents replaced (natural aggregate
replaced by recycled ceramic aggregate).

It is noteworthy, however, that the level of content substitution did not affect the bond stress as sharply as it affected the mechanical properties of each of the evaluated concrete mixtures. Table 5 and Figure 7 compare concrete strength and bond stress results obtained in this study with the ones calculated in accordance to national and international standards (Equations 1 and 2). The model proposed by Siempu and Pancharthi (2017), which uses the previously indicated Equation 3, is also included.

Even though the replacement of the natural aggregate by the recycled ceramic aggregate lead to a bond strength reduction, results for average bond stress were always superior to those predicted by the standards. These results suggest that the substitution of natural coarse aggregate by recycled aggregate from ceramic waste can be viable when it comes to maintaining the bond between steel bars and concrete, even for the 100% (total) content replacement level.

It is also noteworthy that the Siempu and Pancharthi, (2017) model produced unsatisfactory results when applied to the concrete mixture with total natural aggregate replacement (S100). The estimated bond stress value was much higher than the experimentally obtained average bond stress. It is possible that the authors' model is not suitable for the analysis of concrete mixtures employing aggregates taken exclusively from red ceramics, as in the case of this study.

Table 5
Bond stress results
for evaluated concrete mixtures.

Type	f_{c28} (MPa)	τ_{bm} Average (MPa)	τ_{br} Maximum (MPa) (Eq. 3)	Siempu Pancharthi 2017 (MPa) (Eq. 2)	EUROCODE 2/2004 (Eq. 1)
REF	30.00	17.43	20.91	-	7.52
S40	26.22	13.57	16.59	-	5.92
S100	19.04	8.72	13.86	17.44	5.02

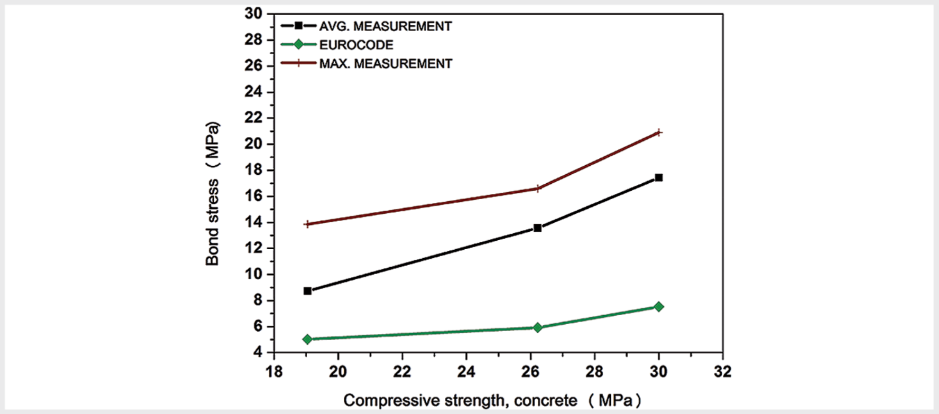


Figure 7
Bond stress compared
with compressive strength.

Figure 7 shows an experimental trend that is also expressed in the standards. Bond stress decreases as a function of reduction in compressive strength of the concrete mixture in question. Thus, a 36.5% variation in compressive strength corresponds to a 49.9% decrease of average bond stress (for the 100% replacement).

Also worthy of notice is the fact that values stipulated by the evaluated regulatory codes are always lower than the experimentally obtained tests, even in the instance of total substitution. This fact indicates that current regulatory procedures, concerning bond between steel bar and concrete, can be employed in the design of structural reinforced concrete elements containing recycled ceramic aggregate.

6. Conclusions

This study evaluated the bond strength between steel rebar and concrete made with ceramic waste aggregate aiming at the use of this alternative mixture in the production of structural reinforced concrete elements. This evaluation was conducted in the laboratory, according to the standard proposed by RILEM-FIP-CEB (1978). As expected, concrete mixture samples showed a decrease in compressive strength after the natural coarse aggregate was replaced by recycled ceramic aggregate. For a complete replacement of the natural aggregate by the recycled aggregate this reduction was 36.5%.

Decrease of the concrete-steel bar average bond stress (τ_{bm}) followed the same pattern regarding levels of substitution. This reduction was also sharp: 49.9% for a concrete mixture that presented a 36.5% reduction in compressive strength (complete natural aggregate replacement).

Maximum bond stress (τ_{br}) and average bond stress (τ_{bm}), even for the 100% substitution sample, were always above the values estimated in national and international standards (NBR 6118:2014 and EUROCODE 2:2004, respectively). This leads us to believe that conventional design procedures for a reinforced concrete element, regarding steel-concrete bond, can be applied to structural reinforced concrete elements made from concrete mixtures with recycled ceramic aggregate in their composition.

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