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Carbonation in Concrete with Recycled Concrete Aggregates

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ABSTRACT

The use of recycled aggregates obtained from the processing of construction and demolition waste has been applied increasingly. The usual alternative for recycling crushed concrete from building demolition is as granular sub-base layers in road pavements and drainage, but more recently recycled aggregates have been used as aggregate in concrete. There are many researches and reports about the fresh and hardened properties of concrete made with recycled concrete aggregate, but there is insufficient knowledge about the durability of this concrete. This paper discusses the performance of concretes with recycled concrete aggregate submitted to carbonation. Concrete with different strengths (18, 37 and 50MPa) were produced, in laboratory, crushed and as recycled aggregates were used in different mixture proportions (25%, 50%, 75% and 100%) in a 32.5MPa concrete. After cure and humidity equalization, they were submitted to accelerated carbonation (chamber with 1% CO_2 and 70% RH). Results indicate that higher amounts of recycled concrete aggregates increase the carbonation depth, when using recycled concrete aggregates from concrete with lower strength than the new concrete, but recycled concrete aggregates from concretes with higher strength do not result in lower durability due to carbonation.

KEYWORDS

Carbonation, Recycled aggregates, Durability.

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1 INTRODUÇÃO

Construction and demolition waste (CDW) in Brazil account for approximately 50% of all municipal solid waste [Ângulo et al. 2003]. This amount comes from civil construction work, such as new construction, renovations and demolitions. CDW consists of residues of materials used throughout the construction process. In Brazil, the recyclable CDW are denominated, according to The National Council on the Environment Resolution CONAMA 307 [Brasil 2003], 'Class A waste', that is composed of ceramic, mortar, concrete and soil. Among these, the present study opted for concrete waste, due to its mechanical properties, which provide a good utilization expectation, in the form of aggregate, in a new concrete matrix. Studies using concrete aggregates [Butler 2003, Bazuco 1999, Levy 2001] evidence their good mechanical characteristics. However, there is few data on the durability of this material. Durability is a very relevant issue when the intention is to design a structure with long lifecycle, low maintenance and therefore, more sustainable. In this study the durability of concrete with recycled concrete aggregate is evaluated from the perspective of carbonation.

The phenomenon of carbonation of concrete results from the combination of several factors, such as the concentration of carbon dioxide that the structure is subjected to, the type of binders used in the preparation of concrete and the pore distribution of the hardened concrete. Besides the pore network of the concrete, the internal moisture conditions exert a determining factor for reactions to occur, as the pore must be partially saturated to provide a suitable environment for both the dissociation of CO_2 from the atmosphere and the dissociation of the concrete hidroxides, forming calcium carbonate, which precipitates and alters the pH of the concrete. Other factors, such as the temperature of concrete and the presence of microcracks will also interfere in the speed of the phenomenon. The simplified carbonation reaction is shown in Equation 1.

$$Ca(OH)_{2(s)} + CO_{2(g)} \leftrightarrow CaCO_{3(s)} + H_2O_{(l)}$$ **Equation 1**

The carbonation phenomenon affects the integrity of reinforced concrete structures due to a decrease in the pH of concrete, destabilizing the passivating layer that acts as a barrier to protect the steel bars against corrosion. The corrosion process results in the generation of oxides along the steel bar, which results in internal stresses that can overcome the concrete's tensile strength and lead the concrete cover to collapse.

Carbonation in concrete with natural aggregate is a widely studied phenomenon. However, when inserted aggregate with different characteristics, such as high porosity aggregates, the properties of the aggregate and the alterations that might occur in the mortar and in the paste-aggregate interface may result in substantial changes in the penetration speed of the carbonation front.

2 METHOD

This study performs a comparison in the behavior of compressive strength and carbonation depth in concretes made with recycled concrete aggregates (RCA) The RCA were obtained from the crushing of concrete that was made in laboratory, which compressive stregnth were 18 MPa, 37 MPa and 50 MPa. The replacements of natural aggregate to RCA were performed at different substitution percentages (25, 50, 75 and 100%), and because of the aggregate porosity was carried out a pre-wetting process in different percentages 0, 25, 50, 75 and 100%, related with RCA's total water absorption. The involved variables are part of a fractional factorial experimental project.

2.1 Materials

It was used Portland cement (high-early strength) in order to obtain a high hydration degree until the scheduled date for the recycling of the concrete (63 days). As fine aggregate was used a quartz sand with fineness modulus of 2.73; maximum dimension of 4.8 mm; specific gravity of 2.49 g/cm³ and bulk density of 1.61 g/cm³. Crushed basalt was used as natural aggregate, fineness modulus of 6.69; maximum dimension of 19 mm; specific gravity of 2.75 g/cm³ and bulk gravity of 1.49 g/cm³. The particle size distribution is between 12.5 and 25 mm. Figure 1 presents an image of the recycled concrete aggregates.

Figure 1. Recycled concrete aggregates.

2.2 Production and Caracterization of Recycled Concrete Aggregate

The recycled concrete aggregate was obtained from the crushing of concretes that were produced in laboratory. The aim of concrete production in laboratory was to know all the characteristics of this by-product, the aggregate, and as consequence to reduce the possible unknown variables. Also it was a oppotunity to simulate the situation of prevailing in precast concrete plants.Three different concretes were produced and their characteristics are presented in Table 1. The concretes were molded into cylindrical specimens, 100 mm (diameter) x 200 mm (high) and maintained submerged during the cure period (63 days). The mortar content adopted for the concrete was α = 49% that generated a satisfatory level of workability of 100 ± 20 mm. The compositions of original concrete are presented in Table 1 and the physical characteristics of the aggregates obtained by them are presented in Table 2.

Table 1. Composition of original concretes.

w/c ratio	*Sand content (kg)*	*Natural Aggregate content (kg)*	*Cement Content (kg)*	*Compressive strength (28 days - MPa)*
0.85	21.75	28.36	5.50	18
0.56	18.40	28.21	8.70	37
0.43	16.54	30.75	13.00	50

* In order to nominate the different types of recycled concrete aggregates was decided to use the original concrete resistance as definition.

Table 2. Physical characteristics of recycled concrete aggregates.

RCA	*Maximum size (mm)*	*Fineness modulus*	*Specific gravity* (g/cm³)	*Total Absorption* (%)
18 MPa	25	7.68	2.50	8.49
37 MPa	25	7.61	2.47	6.07
50 MPa	25	7.70	2.49	5.24

After a cure period of 63 days (to obtain a high degree of hydration), the concrete specimens were crushed in a in a jaw crusher. With a sieving process, the aggregates were divided into fractions of the following sizes: coarse (between sieve # 25 mm and sieve # 4.8 mm) and fine (between sieve # 4.8 mm and sieve #0.15 mm), just the coarse fraction was used. The particle size distribution of the RCA is between 12.5 and 25 mm. The crushed concrete was kept dry before sieving to avoid any carbonation in the aggregates until use them in the new concrete mixtures. To maintain the dry condition, the aggregates were kept in shut plastic containers.

2.3 Production of Concrete with RCA

The materials used to produce the concretes with RCA were the same that were used to produce the original concrete of RCA. However, it was necessary to change the mortar content from α = 49% to α = 53%.The trace obtained from the reference concrete , using such conditions, was 1:3,13:3,67 (cement : fine aggregate : natural coarse aggregate, respectively) and w/c ratio of 0.64. Past 28 days of submerged cure, the reference concrete obtained compressive strength of 32,5 MPa. The different RCA were introduced into the new concrete matrix in levels of 25, 50, 75 and 100% substitution of natural aggregate to RCA. The replacement was made considering the compensation of the RCA volume through the specific mass of RCA and natural aggregates, as shown in Equation 2.

$$M_{RCA} = \frac{M_{NA}}{\gamma_{NA}} \times \gamma_{RCA}$$

Equation 2

Where: M_{RCA}= mass of recycled concrete aggregate; M_{NA} = mass of natural aggregate; γ_{RCA} = specific mass of RCA; γ_{AN} = specific mass of natural aggregate.

The porosity of the RCA was compensated through the execution of pre-wetting, which was performed also with different levels (0, 25, 50, 75 and 100%) in a room with controlled temperature and humidity (T = 21°C ± 2°C; RH 90 ± 5%). To maintain the workability in 100 ± 20 mm, were performed adjustments, then the final water/cement ratios were modified. Such adjustments (initial water content - or + final water content) created a new independent variable in the project with random levels.

2.4 Production of Specimens of Concrete with RCA

Cylindrical specimens (100 x 200 mm) were molded in order to evaluate compressive strenght according to the Brazilian standard ABNT NBR 5739:2003. To evaluate the carbonation profile, were used prismatic specimens (60 x 60 x 180 mm), compacted in horizontal vibrating machine and kept in a submerged cure for 63 days. After the cure the specimen were submitted to drying and stabilization of the internal moisture content, in order to achieve an apparent internal moisture content of 70%, according to the modified RILEM TC 116 PCD procedure. The modification is related to the period of stabilization (RILEM – 14 days; the present work = 28 days) and the internal moisture estimate method. In this work the determination of apparent internal moisture was made using the difference of the mass between a saturated specimen and a dried specimen. The specimens were kept in oven (50°C) until the loss of 30% of the mass difference, reaching in a internal apparent moisture of 70%.

The phase of the redistribution of moisture aims to homogenize the internal moisture of the prisms. Afterwards, the prisms were kept in a chamber for the accelerated carbonation test, adopting exposure conditions of 1% CO_2 and relative humidity of 70%. The prisms were kept under these conditions for 147 days, and then the carbonation depth was determined, using phenolphthalein and an image analysis with the software *Image Tool 3.00*, as seen in Figs. 2 and 3.

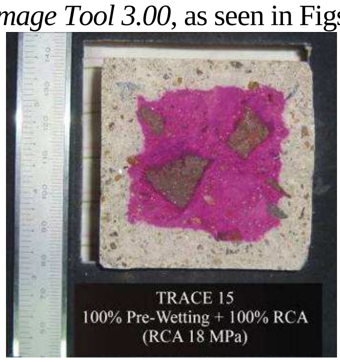

Figure 2. Carbonated specimen.

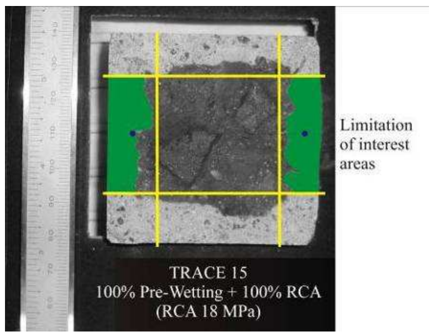

Figure 3. Identification of the carbonated area.

From the data obtained through the accelerated test, the behavior of the advance of the carbonation front over time was determined and the influence of the presence of recycled concrete aggregates in new concrete matrix was examined.

3 PRESENTATION AND DISCUSSION OF RESULTS

3.1 Compressive Strength

The results of compressive strength are presented in Table 3. Through analysis of variance (ANOVA) was possible identify the significant influence of the variable RCA content and type of aggregate.

Table 3. Average results of compressive strength from executed combinations (avarage of 3 specimen).

*RCA Type**	*Recycled concrete aggregate content*	*Pre-wetting rate*				
		0%	*25%*	*50%*	*75%*	*100%*
18 MPa (w/c 0.85)	*25%*		33.3		27.2	
	50%	29.9		30.4		28.5
	75%		27.9		26.6	
	100%	26.8		25.5		25.6
37 MPa (w/c 0.56)	*25%*	29.5		35.4		32.7
	50%		31.6		33.7	
	75%	30.8		29.3		27.1
	100%		26.7		30.7	
50 MPa (w/c 0.43)	*25%*		32.7		25.8	
	50%	33.5		34.3		33.8
	75%		28.2		25.7	
	100%	31.1		32.6		28.8

* The reference concrete has presented a compressive resistance of 32.5 MPa.

The data show that the concrete with recycled concrete aggregate, which presents porosity equal or lower than the new matriz, in general, obtained a similar resistance or presented some addition of resistance (+ 8%). In concrete with RCA porosity higher than the new matrix,it has presented a reduction of the compressive resistance, about less than 10%.

3.2 Carbonation Depth

The results obtained from the accelerated carbonation test are presented in Table 4 and were treated statistically. It was used the software StatGraphics Centurion Data Analysis, to check which variables have significant influence on its behavior.

Table 4. Average results of carbonation depth (mm) after 147 days to CO_2 exposure.

*RCA Type**	*Recycled concrete aggregate content*	*Pre-wetting rate*				
		0%	*25%*	*50%*	*75%*	*100%*
18 MPa (w/c 0.85)	*25%*		10.6		8.4	
	50%	8.3		9.3		11.0
	75%		11.6		11.9	
	100%	13.1		11.8		12.1
37 MPa (w/c 0.56)	*25%*	9.3		9.7		8.4
	50%		11.3		10.3	
	75%	11.4		10.2		9.8
	100%		10.5		11.4	
50 MPa (w/c 0.43)	*25%*		10.5		8.8	
	50%	10.5		8.7		8.8
	75%		9.7		8.8	
	100%	8.9		10.3		9.7

* The reference concrete presented a compressive resistance of 8.8 mm.

** Average of 4 specimen.

The regression equation obtained (presented in equation 3) had a coefficient of determination (r2) of 0.97, that is, the proposed model explains 97% of the data observed for the carbonation phenomenon over time. A significance level of 99% was adopted.

$$Cd = EXP \times (b0 + (b1/FC) + (b3/WCR) + (b12 \times ARC/FC) + (b23 \times ACF/ARC)) \times (T\hat{\ } b4) \qquad \textbf{Equation 3}$$

Where: Cd = carbonation depth (mm); FC = resistance of original concrete of aggregates (MPa); WCR= final w/c ratio; ARC = aggregate replacement content (%); T: time; bn = equation constant.

From this regression, the behavior of different admixtures was estimated with theoretical w/c ratios of 0.45, 0.65 and 0.75, as a result of a independent variable with random levels, as seen in Figure 4.

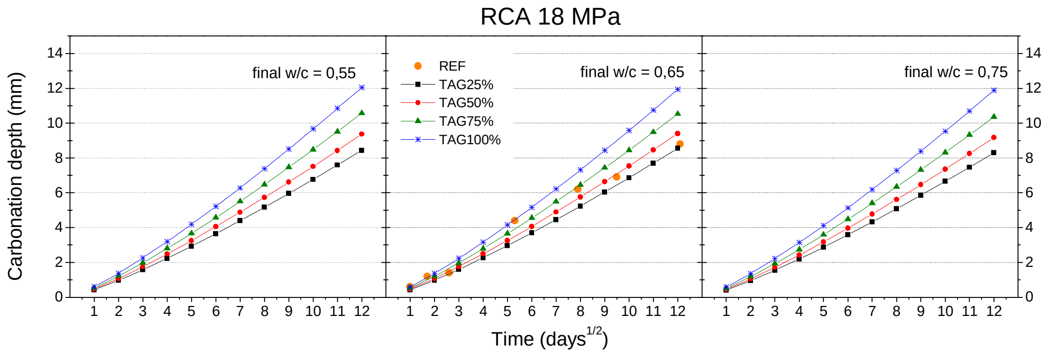

Figure 4. Behavior of concrete with RCA versus carbonation during 147 days.

The variables that most had influence on the carbonation behavior were *replacement content* and *type of aggregate*. *Replacement content* has generated an expected result. The more RCA content in the mixture, the higher will be the carbonation depth. The *type of aggregate* had a significant influence over carbonation behavior. Through the utilization of aggregates with known characteristics, it was possible to identify the influence of the type of the RCA in the phenomenon of carbonation.

As can be seen in Fig. 5, for every type of aggregates has occurred a high variation in the carbonation depth. However, when only the aggregate 'RCA 18 MPa' was analyzed, their variation wass meaningly higher than the other mixtures. This behavior would be assigned to original porosity of this material. Meanwhile the 'RCA 37 MPa' and 'RCA50 MPa' presented a smaller variation and a lower carbonation depth at the final test period (147 days).

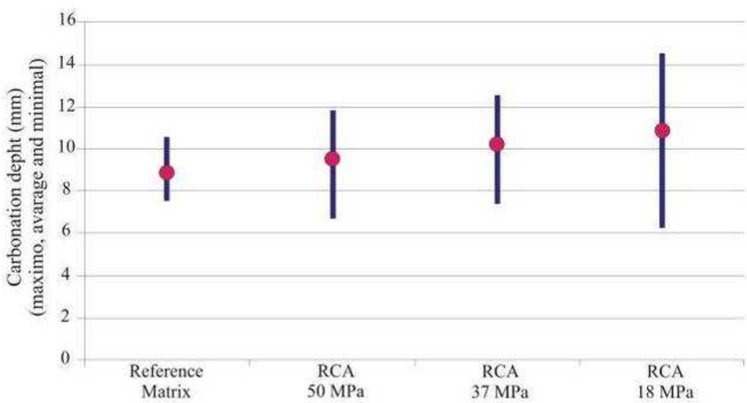

Figure 5. Behavior of carbonation depth related to the type of aggregate.

Considering the matrix where the aggregates are inserted, as presented in Fig. 6, it can be verified that in the concrete with 50 MPa aggregate there was no change behavior in the carbonation front, independently of the amount of aggregates in the mixture. As well as when it was used 37 MPa aggregates in all admixtures studied, there was a small influence of the recycled aggregate content. The highest differences appeared with higher recycled aggregate content in the mixtures. However these mixtures preserved a similar behavior.

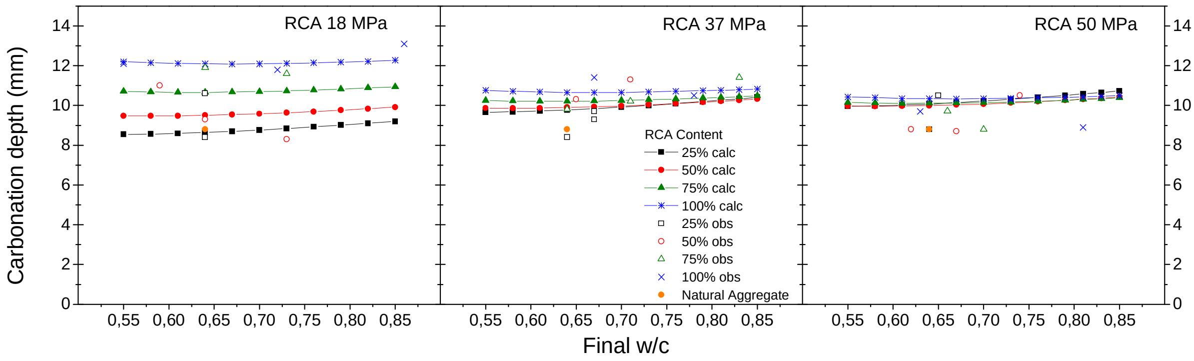

Figure 6. Carbonation depth considering different aggregates content in matrix with different w/c ratio.

The presence of 'RCA 18 MPa' leads to increase the carbonation depth and the differences of carbonation depth related with the RCA content are more expressive among the concretes. In this case the aggregate content becomes a significant factor that can turn unfeasible the use of the aggregates in a new concrete.

Apparently, there is no difference of carbonation depth in concretes with the same content of recycled aggregate, when using aggregates from original concretes of 37 and 50 MPa, as well as with different final water/cement ratios. In relation to the reference concrete, those ones made with RCA 37 MPa have carbonated a little more than the reference concrete. The results are similar to Levy [2001], who performed an accelerated carbonation test in samples of concrete with RCA 35.5 MPa in a matrix with fc= 32.5 MPa. Concretes with a RCA 50 Mpa carbonated even less than the reference concrete. In the latter situation, where RCA 18MPa was used, a material with significantly more porous than the matrix, a higher carbonation depth was found, it was also noticed a significant influence on the amount of substitution of natural aggregate by RCA 18 MPa. The result is consistent to Wu and Song's [2006] apud Li [2008], which concluded that, the higher the RCA content, the higher the carbonation depth. The authors found out that the carbonation depth is up to 62% higher than the reference concrete, for an aggregate substitution content of 60%, and have asserted that the high porosity of the aggregate is responsible for this outcome. Gomes and Brito [2009] claim that the carbonation depth for concretes with up to 50% RCA content, results in a small increase in carbonation depth, in the order of 10% higher than the reference concrete.

4 CONCLUSIONS

Independently of the type and content of RCA, the new concrete tends to be more porous than the reference one and consequently more susceptible to carbonation. Concretes with RCA 18 MPa presented a carbonation depth until 1.8 times greater than the reference concrete. With RCA 37 MPa the carbonation depth was 1.3 times greater than the carbonation depth of reference concrete and concrete with RCA 50 MPa the carbonation depth was 1.2 times greater. In this study, a concrete with RCA of equal or higher porosity (37 and 50 MPa) than the new matrix (32.5 MPa), the carbonation depth in 147 days is similar to the reference concrete. However, when using high porosity RCA (18 MPa), the carbonation depth shows higher dispersion of results and is substantially higher than the reference concrete (approximately 50%).

The increase in carbonation depth is directly proportional to the increase in RCA content. For concrete with RCA of 37 MPa or 50 MPa, the carbonation depths found out for each substitution content, were proportional one another. When using RCA from a more porous concrete (18 MPa), the differences in carbonation depth become more expressive. The studied carbonation depths were in the range of 9.5 mm, for 25% and 50% content of RCA, changing to 12.1 mm for 75 and 100% content of RCA, an increase of 27% in the carbonation depth related to the RCA content.

An important information about the method tested is relative to the exposure time. By using concrete with RCA until the first 28 days the results tend to be quite similar to the reference concrete but afterwards, between 63 and 91 days such a behavior tends to change.

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