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Chloride Ions Penetration in Concrete with Recycled Concrete Aggregates

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ABSTRACT

The use of construction and demolition waste (CDW) aggregate is being a practice that starts to gain importance, both for the environment and the society in general. For use on structural concrete and on pre-cast concrete, the recycled concrete aggregate is mostly indicated. Some kinds of recycled concrete aggregate can be generated with the renovation and demolition of concrete structures. The difference among these aggregates is related to the compressive strength and porosity that they have, which can be variable. Both aggregate compressive strength and porosity will influence on the fresh or hardened concrete properties. The greater porosity of recycled concrete aggregate will influence on its absorption as well on the water demand for the maintenance of the concrete slump. A pre-wetting of recycled aggregate is generally adopted, for this case, as a proceeding to compensate its absorption, not existing nonetheless any consensus related to what amount of pre-wetting water must be utilized. The aim of this essay is evaluating the behavior of chloride penetration of concrete prepared with recycled concrete aggregate. The concrete production was effectuated with three different recycled concrete aggregate, from three concretes with different compressive strengths (18, 37 and 50 MPa), with five contents of recycled concrete aggregate in replacement to the natural aggregate, as well with five water amounts to pre-wetting of recycled concrete aggregate . The resistance to chloride ions penetration was conducted according ASTM C-1202 Method. The results were analyzed by statistical methods and indicate that the independent variables and their interaction have a significantly influence on resistance to chloride ions penetration.

KEYWORDS

Recycled concrete aggregate, Concrete waste, Chloride ion penetration, Durability, Recycling.

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1 INTRODUCTION

The use of recycled aggregates from construction and demolition waste (CDW) is an increasingly important practice, as it can benefit both the environment and the society. In generaI it has been a consensus in many studies that concrete is the most indicated CDW for use as an aggregate be it in structural concrete or in the production of pre-cast concrete. By being the water absorption of recycled coarse aggregates greater than it is in conventional aggregates, there is a need to compensate for any eventual water absorption from the new concrete mixing water by the new recycled material. According to Vieira [2003] the high water absorption rate in recycled aggregates must be discussed. Concrete made with such a type of aggregate which is more porous, will demand a larger amount of water to achieve the same workability that the conventional aggregates do. Due to this, many authors have elaborated concrete mixtures using different amounts of water so that both the mortar slump and the workability can be satisfied. However the water-cement ratio is altered, influencing on the strength of these concrete, making impossible the comparison between the conventional concrete and the recycled aggregate concrete. In fact, what can be observed is that the performance of concrete with recycled aggregate, regarding to workability, is considered unsatisfactory due to loss of slump, especially with the increase in percentage of coarse aggregate in the mixture. For aggregates previously saturated before mixing, there will be water mobilization in the fresh mixture, once the water absorbed by the aggregate can be considered free water and, therefore, when mobilized to the fresh mixture it will cause an increase in the w/c ratio in the transition zone, a fact that augments voids, and results in reduction of strength [BUTTLER, 2003].

Villagrán-Ziccardi et al. [2008] analyzed the penetration of chloride ions plus chloride, combined in a concrete made with recycled aggregate from concrete. There have been levels of 50 and 75% of natural aggregate in recycled aggregate, with the ratio w/c varying from 0.35 to 0.60 plus two types of cement. The residual concrete employed to obtain the recycled aggregate had different strengths and was not segregated on basis of its resistance, since the absorption of the RCA was of 4.6% versus 0.3% of the granite aggregate. The slump test results varied from 120 a 60 mm. The authors, at that stage of the study, concluded that the w/c ratio has more influence on the penetration rate of chloride ions than on the porosity of the RCA.

According to Eguchi et al [2007], high levels of recycled coarse aggregates, in concrete mixture, reduce the compressive strength and the modulus of elasticity, increasing drying shrinkage. Concrete quality must be assured from the adjustments of an optimal substitution content of a natural aggregate for a recycled aggregate, turning the workability and the structural performance compatible with the conventional concrete performance. Poon and Kou [2006], studying compressive strength, pore distribution and chloride ions penetration in recycled concrete aggregate concluded that the increase in RCA content reduces its strength, however this reduction can be compensated by reducing the ratio w/c in the mixture. Total porosity and average pore diameter increase with the high content of RCA. However, high contents of RCA linked to the employment of low ratios of w/c plus 25% of fly ash reduces chloride ions penetration, also reducing pore diameter and total porosity.

Therefore, further studies are needed to indicate the influence of the resistance of recycled concrete behavior made of recycled aggregate concrete incorporated into the new matrices of concrete, as well the influence of the amount of aggregate replacement and the influence of a pre-wetting to compensate for the water absorption of RCA. This study evaluated the influence of type and content of RCA in the penetration of chloride ions in concrete made with RCA, as well as the influence of pre-wetting rate to compensate the water absorption of the waste.

2 METHODS

2.1 Analysed Variables

Given the target of the present essay the analyzed response variables have been “total charge passed”, which show the resistance of the concrete to chloride ion penetration, and “compressive strength”. The control factors have been: “recycled concrete aggregate content”, with levels of 0, 25, 50, 75 e 100%; “compressive strength

of recycled concrete aggregate", with fixed levels of 18, 37 e 50 MPa; "rate of pre-wetting"', with fixed levels of 0.25, 50, 75 and 100% of total absorption of RCA. The control variables have been tested through an experimental project of the fractionated factorial type.

2.2 Materials

A commercial Portland high early strength type CP V-ARI according to ABNT NBR 5733 [1991] was used, with density of 3.12 g/cm³. It was used as fine aggregate the quartz sand, with a fineness modulus of 2.73; characteristical maximum dimension of 4.8 mm, density of 2.49 g/cm3, and unit mass of 1.61 g/cm3. As coarse aggregate it was used crushed gravel of basalt, with granulometry comprehended between 12.5 and 25 mm, fineness modulus of 6.69, characteristical maximum dimension of 19 mm, specific mass of 2.75 g / cm ³, and unit mass of 1.49 g / cm ³. More characteristics of the materials can be found in Troian [2010].

2.3 Recycled Concrete Aggregates

The concrete recycled as RCA was produced in laboratory, in order to obtain three different compressive strength levels. The material used to produce this concrete was the same materials from the new matrix where the RCA were inserted. The physical characteristics of concrete and RCA are presented in Table 1, the water absorption was measured according to Werle et al. [2010].

Table 1. Physical characteristics of recycled concrete aggregates.

w/c ratio	*Compressive strength (28 days - MPa)*	*Maximum size (mm)*	*Fineness modulus*	*Specific gravity* (g/cm³)	*Total Absorption* (%)
0,85	18	25	7,68	2,50	8,49
0,56	37	25	7,61	2,47	6,07
0,43	50	25	7,70	2,49	5,24

2.4 Concrete Production with RCA

The concrete used as reference on which partial and total replacements of natural aggregate by RCA were performed, has pre-established workability of 100 ±20 mm, with a proportion of cement: fine aggregate: coarse aggregate 1:3, 13:3, 67; w/c ratio 0.64 and 28 days strength of 32.4 MPa. The slump test was defined in 100±20 mm and should be assured in all mixtures. When the RCA was introduced, with different pre-wetting rates, it was necessary to adjust the mixing water with reductions or augmentations, so that the slump was assured. Such an adjustment generated a concrete matrix with a modified w/c ratio, if compared to the reference concrete, obtaining different values of w/c ratio, for each combination of variables. The result was a new independent variable which was defined as final w/c, that is (initial w/c + adjustment w/c), with random levels.

2.5 Experimental Methods

The concrete here studied was characterized regarding to axial compression strength according to the Brazilian standard ABNT NBR 5739 [2003]. The ASTM C 1202-07 - Rapid Chloride Ions Penetration Test - RCPT was used to determine rapid chloride ions penetration.

3 RESULTS

3.1 Compressive Strength

The analysis of variance (ANOVA) has showed that only the RCA strength and the RCA content can affect significantly the concrete compressive strength. The influence of the type of aggregate on strength is shown in the box-plot chart in Figure 1.

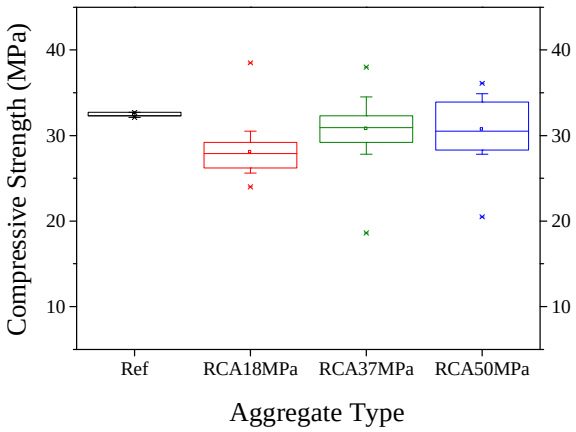

Figure 1. Effect of compressive strength of RCA on compressive strength of new concrete.

3.2 Chloride Ion Penetration

The resulting total charge for each combination of variables is presented in Table 2. The statistical analysis of the observed data for total charge passed in concrete was measured through multiple linear regression.

Table 2. Chloride ion penetration.

*RCA Type**	*Recycled concrete aggregate content*	*Pre-wetting rate*				
		0%	*25%*	*50%*	*75%*	*100%*
18 MPa (ABS 8,49%)	*25%*		4924		5110	
	50%	8607		5814		6222
	75%		7946		9542	
	100%	9430		9158		9963
37 MPa (ABS 6,07%)	*25%*	4795		5414		8388
	50%		5541		5846	
	75%	5405		6601		7380
	100%		8043		8680	
50 MPa (ABS 5,24%)	*25%*		4742		4806	
	50%	6237		5634		5749
	75%		6312		6820	
	100%	6847		6832		8142

* The total charge for plain concrete is 4077 Coumlombs.

The resulting total charge for each combination of variables is presented in Table 2. The statistical treatment analysis of the observed data for total charge passed in concrete was measured through multiple linear regression. The analysis of variance (ANOVA) of the calculated model is presented in Table 3 and the calculated parameters for the independent variables analyzed (factors) are presented in Table 4. In this analysis the variable called 'aggregate type' was represented by total water absorption (ABS) of the recycled aggregate and the levels of study were presented on Table 2. The value of 'p' inferior to 0.01 shown in Table 3 indicates that the relation between variables is statistically significant at a confidence level of 99%. The obtained coefficient of determination r^2 of 0.8834 shows that the model explains 88.34% of the values variability observed for total charge passed. It is emphasized that the variability of the test proposed by ASTM C-1202-07 is high.

Considering the variables analyzed in the models and their interactions, the results in Table 6 indicate that the aggregate substitution content (ASG) and the pre-wetting rate (PWR) are statistically significant at a confidence level of 99%, as they present "p" with value inferior to 0.01. The final w/c ratio (WCR) shows significant effect on the total charge passed, in form of a quadratic term, but at a confidence level of 90%, once

the "p" value for this factor is 0.08. Likewise, it was found that the interaction of the analyzed ABSxASG variable shows significant influence on the total charge passed. This result shows that such a type of aggregate, in this analysis represented by its absorption (ABS) only has significant effect on the variable when associated to the aggregate substitution content (ASG). The interactions between ASGxWCR plus PWRxWCR have been control factors which did influence significantly the behavior of the total charge passed, which evidences the resistance to chloride ion penetration at a level of 99%, resulting in "p" value lower than 0.01, i.e., it was proved that the interaction between this variables is statistically significant. Equation 1 shows the model used for total charge passed.

Table 3. ANOVA for chloride ion penetration model.

Source	*DF*[a]	*SQ*[b]	*MQ*[c]	F_{calc}	*Significance - p*
Regression model	9	7,1532	7948	17,68	0,0000
Residual	21	9,44282	2,50	1,21	
Corrected total	30	8,09748	2,49	1,21	

[a] Degrees of freedom; [b] Sum of squared.; [c] Squared mean.

Table 4. Regression parameters for the factors studied for total charge.

Factor	*Parameter*	*Estimate*	*Standard error*	*t-test*	*p*
Constant	b0	-1864,92	3514,57	-0,530626	0,6012
ASG	b1	291,143	92,0107	3,16423	0,0047
PWR	b2	-339,905	84,4363	-4,02558	0,0006
ASG^2	b3	0,602833	0,223394	2,69852	0,0135
PWR^2	b4	0,903205	0,213384	4,23277	0,0004
WCR^2	b5	14867,5	8232,41	1,80597	0,0853
ABS*ASG	b6	9,73207	1,46102	6,66117	0,0000
ASG*PWR	b7	0,837158	0,257582	-3,25007	0,0038
ASG*WCR	b8	-508,871	150,242	-3,38701	0,0028
PWR*WCR	b9	-460,893	110,221	4,18152	0,0004

$$Q = -1864{,}92 + 291{,}143\times ASG - 339{,}905\times PWR + 0{,}602833\times ASG^2 + 0{,}903205\times PWR^2 + 14867{,}5\times WCR^2 + 9{,}73207\times(ABS\times ASG) - 0{,}837158\times(ASG\times PWR) + 508{,}871\times(ASG\times WCR) + 460{,}893\times(PWR\times WCR) \quad \textbf{Equation 1}$$

Where: Q = Total Charge (Columbs); ASG = aggregate substitution content (%);PWR = pre-wetting rate (%); WCR = final w/c ratio; ABS = total water absorption of recycled aggregate (%).

The graphs in Figures 2, 3 and 4 show the behavior curves for total charge passed after 6 hours, for three fixed levels of final w/c ratio, ranked in lowest and highest values of final w/c ratio seen in the experimental program.

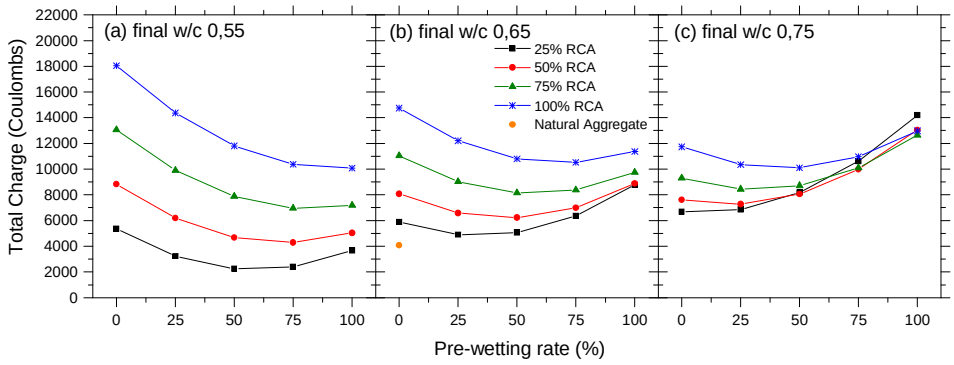

Figure 2. Total charge for concrete with RCA 18 MPa.

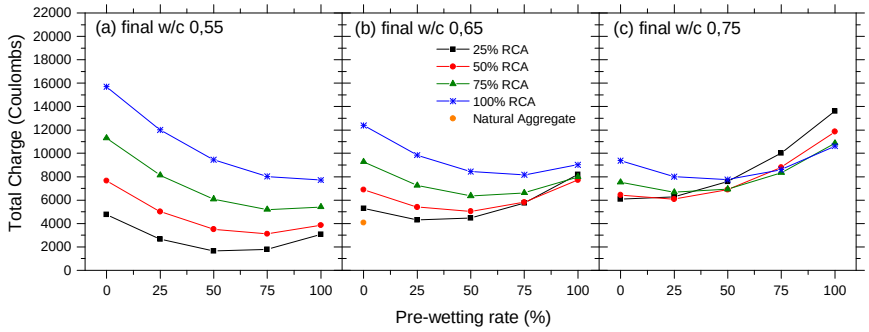

Figure 3. Total charge for concrete with RCA 37 MPa.

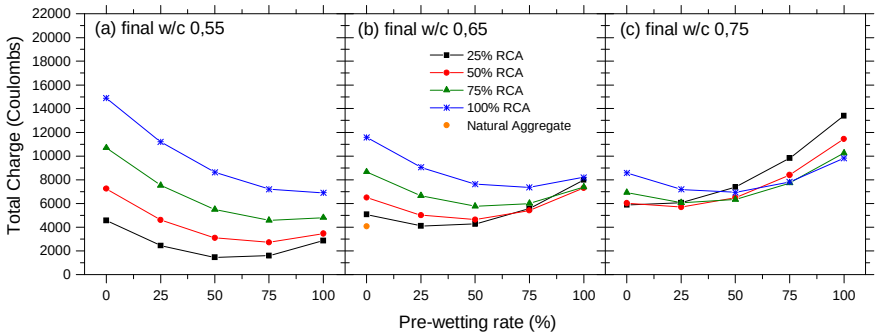

Figure 4. Total charge for concrete with RCA 50 MPa.

The concrete with RCA of 18 MPa, pre-wetting values up to 50% and substitution content (ASG) exceeding 50%, had higher total charge passed when w/c ratio was lower, as seen in the curves of the adjusted models, shown in the graphs in Figure 2 (a) and (b). However, for w/c ratio of 0.75, when pre-wetting rates exceed 50%, the lowest substitution contents show higher total charge passed (Figure 2(b)). The concrete with RCA of 37 MPa (Figure 3) and 50 MPa (Figure 4), had the same behavior trend once that the total charge passed does not show significantly differences when comparing concrete with these types of aggregate. However, regarding the concrete with 18 MPa RCA, both showed a significantly difference.

The results for total charge passed for concrete produced with 18 MPa RCA show an average increase of 90.15% when compared to the reference concrete. Similarly, the concrete with RCA of 37 and 50 MPa, respectively, showed an average increase of 62.11% and 52.37% compared to the reference concrete (Figure 3). It can also be stated that regardless of the aggregate's strength, the concrete with pre-wetting rate superior to 50%, substitution content of 50% and higher final w/c ratio, had higher values for total charge passed.

Another important aspect is that the higher the w/c ratio of the concrete matrix is, the higher is the charge passed, or, the lower is the resistance to chloride íons penetration; clearly evidenced when (each type of aggregate) is compared to the curves for concrete with w/c ratio of 0.55, 0.65 and 0.75. It is also emphasized that it is possible to analyze the results for the traces produced with final w/c ratio of 0.65, pointing out that this result is similar to the reference concrete's, which was 0.64. The reference concrete, which has the same matrix as the RCA concrete, already has high porosity, and this fact alone results in concrete with high penetration of chlorides, according to the classification ASTM C 1202-07. The averages of the results for total charge passed for concrete with RCA were high and superior to the reference concrete's. This means that the RCA concrete has high penetrability of chloride ions. Or be it, for all levels tested in the variables of the study which are 'type of aggregate', 'substitution content' and 'pre-wetting rate', by simulating a water/cement ratio of 0.65, the concrete showed low resistance to chloride ions penetration.

According to the ASTM C 1202-07 classification, the concrete with total charge of less than 2000 Coulombs have low penetrability of chloride ions, and the concrete with total charge passed between 2000 and 4000 Coulombs have moderate penetrability of chloride ions. Figures 3(a) and 4(a), correspond to the graphs of behavior curves for concrete with final w/c ratio of 0,55, for 37 and 50 MPa RCA concrete, respectively. The curves of substitution content at 25%, and between pre-wetting rate of 50 and 75% , show low penetrability of

chloride ions. Regarding to the concrete with 18 MPa RCA and final w/c ratio of 0.5, the concrete with RCA at 25%, show moderate penetrability of chloride ions. Observing the graphs of total charge passed, for the new concrete with final w/c ratio of 0.65, the behavior trend until 50% PWR is reversed. The interaction between the pre-wetting rate and the final w/c is observed in the change of inflection of the curves, that is, after a 50% amount it increases the total charge passed. However, it was found that the type of aggregate is not determinant when it is used in a matrix with a higher w/c ratio.

Gomes and Brito (2009) by conducting an experimental study similar to this, have evidenced that the concrete with RCA has shown a slightly higher penetration of chloride ions, with maximum differences around 6%, when compared to concrete with natural aggregate. This low reduction in compressive strength so observed by the referred authors may be attributed to the low w/c ratio of the concrete matrix where the RCA was incorporated (ratio of 0,43), while the present study has used 0.64; then this could explain the higher differences compared to the reference concrete. Poon and Kou (2006) showed in their research, that with a reduction of 0.55 to 0.45 in w/c, there was a significantly decrease in penetration of chloride ions, once the volume of pores decreases letting the concrete more impermeable and, in conformity with this, the resistance to penetration of chloride ions increases. The results showed a decreased resistance to penetration of chloride ions, with the increase of recycled aggregate. However, according to the authors this reduction could be compensated with the addition of 25 to 35% of pozzolanic material. Being so, it is evident that the final w/c ratio of the cement matrix strongly influences the behavior of the property in question, and if this experimental program had included other matrices of concrete then, possibly the results would have been more satisfactory.
In general, the statistical analysis indicates that, in average, the higher the RCA substitution content and the pre-wetting rate are, the higher is the total charge passed.

The porosity of the aggregate, evidenced by the RCA compressive strength, shows a critical limit for the penetration of chloride ions, which must be, for experimental conditions, between 18 and 37MPa, because in this interval it is possible to be observed an inflection in the behavior of the ARC concrete. In the concrete with higher RCA strength (37 and 50 MPa) there is no significant difference in total charge passed.

4 CONCLUSION

The resistance to penetration of chloride ions is influenced by the analysed variables. In general, it can be stated that the concrete produced has shown a decrease in resistance to penetration of chloride ions due to the porosity of the RCA, that is, the lower the resistance of the ARC is, in this case 18MPa, the higher is the total charge passed, and consequently lower is the resistance penetration of chloride ions. However, observing the aggregates with higher resistance, in this case above 37 MPa, the values were not significantly different from each other. Another aspect noticed was regarding to the final w/c ratio of the concrete matrix, since the higher the w/c ratio is, the higher is the charge passed, regardless of the RCA type, because when the aggregate is inserted in a matrix that already has high porosity, the resistance of the RCA does not seem to influence the results.

From the regression analysis of the results, it is possible to say that the aggregate substitution content has an important isolated effect on the concrete behavior. However, this variable in interaction with the pre-wetting rate also has an expressive effect, which is reflected by the fact that until 50% of pre-wetting, the higher the percentage of substitution can be (ASG) the greater can be the total charge passed, proving the influence of the substitution content. But when the pre-wetting rate exceeds 50% this behavior does not seem to have significancy, namely, the substitution content does not have a strong influence.

The ‘aggregate substitution content’ also has a significant effect when interacting with the final water/cement ratio of the matrix. It can also be inferred that the percentage of pre-wetting rate (PWR), when exceeding 50% and with higher final w/c, has demonstrated increase in total charge passed of the concrete. Another aspect that can be pointed out is the interaction of the variable PWR with the variable ASG. The traces have represented the lowest percentage of pre-wetting and higher RCA substitution content, consequently, have shown higher values in total charge passed.

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