Durability of Concrete Produced with Recycled Aggregates: A Contribution to Safe and Sustainable Development

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ABSTRACT

This study seeks to evaluate the durability of concrete produced with recycled concrete aggregates. Two types of recycled concrete aggregates were used, coarse and fine. Three different concentrations of recycled aggregates were utilizedin order to produce the concrete samples,: 20%, 50%, and 100%, in substitution of natural aggregates. A point analysis of the results was not performed as this is a simplistic procedure often adopted by most researchers. The analysis was instead conducted using families of concrete, allowing for a broader and more accurate comparison. The comparative performance studies were conducted on three different grades of concrete: 20 MPa, 30 MPa, and 40 MPa. This results of this study demonstrate that increased content of recycled aggregates has an effect on concrete resistivity and on the chloride profile at depths of 1 cm, 2 cm, and 3 cm. The authors think that results are positive, demonstrating the feasibility of using concrete recycled aggregates in the production of new concretes.

Keywords: *durability, chloride profile, resistivity, concrete recycled aggregates.*

INTRODUCTION

This study was conducted in order to contribute to sustainable development in a safe and economically viable manner, with the purpose of analysing the influence of increasing concentrations of concrete recycled aggregates on the durability of the resulting concrete. This article is part of a comprehensive study on the properties of concrete with recycled aggregates [1].

For discussion in this article, two properties considered basic in predicting concrete durability were selected: ionic resistivity and chloride profile upto 3 cm depth.

This experiment produced families of concrete having different concentrations of concrete recycled aggregates, maintaining a constant consistency through use of the slump test (70 ± 10 mm) and comparing the result to those obtained from a reference family produced using only natural aggregates.

The electric/ionic surface resistance is one of the important properties that indicate a higher or lower degree of susceptibility to corrosion of embedded steel reinforcement.

The*Comité Euro-International du Béton* [2] provides criteria for the evaluation of concrete resistivity. The reference intervals are presented in Table 1.

Table 1
Criteria for evaluation of resistivity [2]

Concrete resistivity	Probability of corrosion
< 5 kΩ.cm	Very High
5 to 10 kΩ.cm	High
10 to 20kΩ.cm	Low
> 20 kΩ.cm	Negligible

Helene [3] and Andrade [4] make clear that there are various ways in which steel reinforcement can lose or fail to attain the condition of passivation, thereby corroding and deteriorating the structural component. Although there are several ways in which passivation can be lost, the phenomena responsible for this loss are basically two: carbonation and chloride contamination.

Once the protection is broken and the corrosive process begins, its speed and progress come to depend mainly on the electrical resistivity of the concrete and the diffusion of oxygen in the cathode. Higher chloride content, as well as greater chloride mobility because of the electrochemical field generated by the corrosion cell, can accelerate the speed of corrosion.

It is also worth mentioning the importance of resistivity in situations where concrete is wetted and dried and where simultaneously the risk of salt penetration exists, such as sodium chloride in typical marine environments. In these situations, resistivity affects the risk of deterioration of the structural element, exacerbating the problem of reinforcement corrosion.

MATERIALS AND METHODOLOGY

Blended Portland Cement, comprising of 35% blast furnace slag with a Blaine fineness of 385m²/Kg, a density of 2,990 Kg/m³, and an average compressive strength at 28 days of 39MPa (5,655 psi) for standard mortar with W/C = 0.48 was used in all concrete mixtures, as it is the most commonly used cement in ordinary concrete structures in Brazil.

Fine natural aggregates consist of washed quartz river sand with a density of 2,650 Kg/m³, a fineness modulus of 2.6, and 1.8% water absorption in saturated dry surface(SDS) condition.

Coarse natural aggregates consist ofcrushed granite rock gravel with a density of 2,700 Kg/m³, $D_{max}$of 25mm, a fineness modulus of 7.0, and 0.8% water absorption in SDS.Both aggregates are safe andtypically used in the São Paulo metropolitan area.

The fine and coarse concrete recycled aggregates (FRCA and CRCA) were obtained (crushed) from a homogeneous six-month-old concrete structure, having an average compressive strength of 25MPa (3,626 psi) for an average W/C = 0.66 and a density of 2,320 Kg/m³.

The coarse aggregates had a $D_{max}$of 25 mm and a fineness modulus (FM) = 6.6, while the fine aggregates had a $D_{max}$of 2.4 mm and FM of 2.5. Their composition is a cement paste made with the same blended cement, the same granite as the coarse aggregate, and the same natural quartz river sand as the fine aggregate. The fine and coarse concrete recycled aggregates have a water absorption in SDS condition of 10.3% and 5.6%, respectively.

In order to obtain the recycled aggregates, the old concrete was passed through a jaw crusher and the resulting product was then subjected to a sieving operation. The fractions corresponding to fine and coarse aggregates were used to produce six concrete families, always under laboratory SDS conditions, considering the water to be that absorbed by the aggregates themselves. The results were compared against those obtained from a seventh concrete family, produced exclusively with natural aggregates and called the reference concrete family.

Concrete Mix Proportion

Three dry aggregate/cement ratios by mass were used in the composition of each concrete family:3/1, 4.5/1, and 6/1, all of which maintained the same workability as measured by slump test (70±10 mm). Natural aggregates were replaced by concrete recycled aggregates in proportions of 0%, 20%, 50%, and 100% by weight. A total of seven concrete families and 21 different concrete mix proportions were prepared.

Measured Properties

To measure compressive strength, the procedures recommended by standard ASTM C39 [5] were used, and the resistivity was evaluated according to the ASTM G57 [6] methodology.

Cement consumption, water consumption, the water/ cement ratio by mass, the entrained air content, and the specific gravity of the concrete in its fresh state were determined using conventional methods.

To evaluate the chloride contamination profile, the procedures for sample collection and preparation were those recommended by standard ASTMC-1152[7]. The samples were collected at depths of 1 cm, 2 cm, and 3 cm with the aid of a drill. Each new depth used a drill bit of smaller diameter to avoid contamination from one layer to another. The test specimens used were cubes 10 cm on a side. These were placed in a saline chamber after 60 days, and maintained there for 75 days under the effect of a 5% sodium chloride (NaCl) solution. After this period, the cubes were removed and sample collection was performed.

To evaluate resistivity, four prismatic specimens (20 cm x 20 cm x 8 cm) were moulded. The specimens were held for 14 days in a standard wet room. After the 15th day, the specimens were maintained at laboratory conditions (20°C to 28°C and humidity 65% to 75%) until the test date (182 days). The specimens were submerged in fresh water 72 hours before the test.

RESULTS

Initially, mix design diagrams were constructed for each concrete family, evaluating the influence of the concrete recycled aggregate content on the properties selected for the concrete durability analysis for a given desired compressive strength. In Table 2, the results obtained from the tested lines are presented.

Table 2
Experimentally obtained data for the tested characteristics

Coarse Recycled Concrete Aggregate (CRCA)												
Cement / aggregate	1 / 6.0				1 / 4.5				1 / 3.0			
Recycled aggregate	0%	20%	50%	100%	0%	20%	50%	100%	0%	20%	50%	100%
Natural aggregate	100%	80%	50%	0%	100%	80%	50%	0%	100%	80%	50%	0%
f_{c28} (MPa)	26.5	24.6	26.3	28.6	41.9	40.0	38.5	41.1	48.5	52.4	48.1	50.9
Cement content (kg/m³)	269	307	298	294	363	390	388	373	533	503	519	521
W/C	0.75	0.71	0.72	0.71	0.51	0.51	0.52	0.59	0.40	0.41	0.44	0.41
Chloride content												
0-1 cm%	0.45	0.49	0.77	0.36	0.34	0.45	0.42	0.35	0.30	0.36	0.48	0.27
1-2 cm%	0.17	0.15	0.17	0.18	0.05	0.10	0.04	0.10	0.07	0.05	0.04	0.05
2-3 cm%	0.07	0.01	0.00	0.06	0.01	0.01	0.00	0.02	0.01	0.01	0.00	0.01
Resistivity (kΩ*cm)	16.4	17.7	15.4	13.2	19.1	17.6	19.2	11.8	24.7	21.8	19.6	16.6
Fine Recycled Concrete Aggregate (FRCA)												
Cement / aggregate	1 / 6.0				1 / 4.5				1 / 3.0			
Recycled aggregate	0%	20%	50%	100%	0%	20%	50%	100%	0%	20%	50%	100%
Natural aggregate	100%	80%	50%	0%	100%	80%	50%	**0%**	**100%**	**80%**	**50%**	**0%**
f_{c28} (MPa)	26.5	27.5	27.0	23.3	41.9	36.8	33.8	30.2	48.5	56.1	46.3	46.6
Cement content (kg/m³)	269	305	296	310	363	383	377	365	533	525	519	510
W/C	0.75	0.70	0.75	0.80	0.51	0.58	0.61	0.68	0.40	0.46	0.44	0.47
Chloride content												
0-1 cm%	0.45	0.50	0.60	0.62	0.34	0.42	0.54	0.62	0.3	0.27	0.52	0.55
1-2 cm%	0.17	0.21	0.24	0.31	0.05	0.10	0.16	0.25	0.07	0.03	0.15	0.17
2-3 cm%	0.07	0.05	0.06	0.09	0.01	0.03	0.04	0.07	0.01	0.01	0.07	0.04
Resistivity (kΩ*cm)	16.4	16.7	12.1	7.6	19.1	12.2	8.6	7.0	24.7	18.3	9.9	7.7

Construction of Mix Design Diagrams for Compressive Strength

The first step was the preparation of the mix design diagram (MDN) for each of the seven concrete families; one for the concrete produced only with natural aggregates, called the reference concrete; and six for the concretes produced with recycled aggregates: three (3) coarse recycled concrete aggregates (CRCA) and three (3) fine recycled concrete aggregates (FRCA)[8].

The second step was to utilize the corresponding MDN to obtain the W/C ratio necessary, based on the compressive strength desired, of 20 MPa, 30 MPa, and 40 MPa (2,900 psi, 4,350psi,and 5,800psi).

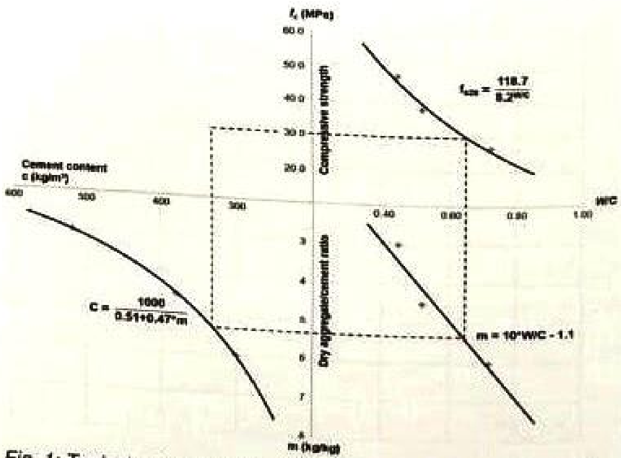


Fig. 1: Typical mix design concrete diagram as anexample (MDN for concrete family 50-50% CRCA)

The third step was to utilize new mix design concrete diagram (MDN) that relate the behaviour of the durability property in relation to the W/C found, as shown in Figures 2 and 3, which present typical examples (MDN for concrete family 50-50% CRCA).

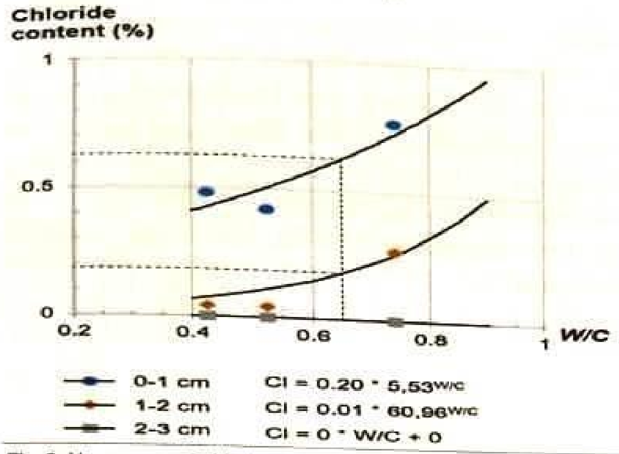
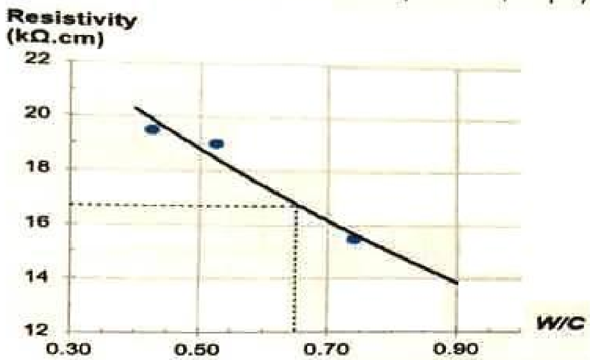


Fig. 2: Nomogram of chloride content at depth 0 to 3cm for the 50%-50% coarse recycled concrete aggregate (CRCA) family. Example for concrete 30 MPa

In the analysis of results, presented in section 4, the evolution of each of the studied properties is analysed in order to evaluate the concrete durability as a function of the type and quantity of natural aggregates substituted by recycled concrete aggregates in order to obtain the compressive strengths desired after 28 days: 20MPa, 30MPa, and 40MPa (2,900psi, 4,350psi,and 5,800psi).



$$\rho = \frac{27.5}{2.2^{W/C}}$$

Fig. 3: Nomogram of resistivity for the 50%-50% Coarse Recycled Concrete Aggregate (CRCA) family. Example for concrete 30 MPa

ANALYSIS OF RESULTS

Development of Resistivity as a Function of the Level of Recycled Concrete Aggregates

The data used to draw the resistivity curves are taken from Table 3 and the respective curves are presented in Figure 4.

Table 3
Consumption *vs.* resistivityas a function of the level of substitution of natural aggregates

Aggregates	(%) of Replacement	Cement Content (kg/cm³)			Resistivity (kΩ.cm)		
	f_{c28}	20 MPa	30 MPa	40 MPa	20 MPa	30 MPa	40 MPa
Natural	0%	179	291	397	13.3	17.0	20.4
CRCA	20%	269	341	407	16.3	17.9	19.3
CRCA	50%	231	329	422	14.8	16.9	18.6
CRCA	100%	190	293	392	10.1	12.1	13.9
FRCA	20%	239	325	404	14.2	15.0	15.8
FRCA	50%	216	330	445	9.8	10.7	11.7
FRCA	100%	266	366	461	7.2	7.4	7.5

The graphs in Figure 4 show that resistivity is reduced as the level of recycled CRCA and FRCA increases.

This fact confirms that the substitution of natural aggregates by those recycled from concrete, even at levels between 20% and 50%, will not be detrimental to concrete durability, since in the worst cases resistivity values will be approximately 12kΩ.cm. According to CEB Bulletin nº192 [2], this value still represents a low risk of corrosion.According to Brito and Gonçalves [9], there is a point of convergence among the various international Standards with regard to the substitution of natural aggregates by coarse concrete recycled aggregate: none of them have any restriction on the substitution of coarse natural aggregates by coarse recycled concrete aggregate at a level of up to 20%, even in concrete with an important structural function.

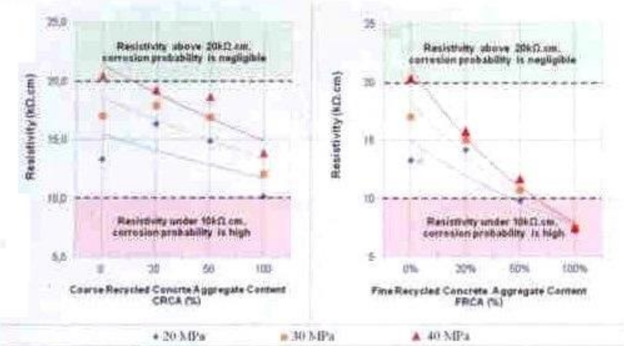


Fig. 4: Evolution of resistivity, with the amount of natural aggregate being replaced by CRCA and FRCA to achieve 20, 30, and 40 MPa at 28 days

Chloride Contamination Profile

The data used to draw the trend curves for chloride profile at depths between 0 and 3 cm were extracted from Table 4. The diagrams are presented in Figure 5, Figure 6, and Figure 7.

Using the equations that represent the mathematical models in mix design diagram bychloridecontent at depth 0 to 3.0 cm, it was possible to calculate the values of the Cl⁻ion concentration for concretes of f_{c28} = 20MPa, 30MPa,and 40 MPa, at depths 0 to 1cm, 1to 2cm, and 2 to 3cm. The trend curves in Figure5, Figure 6, and Figure 7were constructed using these determined values. These curves clearly show that the recycled concrete aggregates (CRCA and FRCA) and the level of substitution of the natural aggregates do not present a significant harmful influence, such that the sustainable concretes using recycled aggregates have a chloride contamination level equivalent to that of the reference concrete.

Table 4
Chloride content at depths of 0 to 3 cm, with the amount of natural aggregate replaced by CRCA and FRCA to achieve 20, 30, and 40 MPa at 28 days

Aggregates	Replacement (%)	Chloride content 0-1 cm (%)			Chloride content 1-2 cm (%)			Chloride content 2-3 cm (%)		
f_{c28} (MPa)		20	30	40	20	30	40	20	30	40
Natural	0%	0.44	0.37	0.32	0.21	0.14	0.09	0.10	0.05	0.02
CRCA	20%	0.52	0.42	0.35	0.18	0.13	0.09	0.01	0.01	0.01
CRCA	50%	0.53	0.47	0.42	0.23	0.13	0.06	0.00	0.00	0.00
CRCA	100%	0.89	0.67	0.51	0.26	0.17	0.10	0.09	0.05	0.03
FRCA	20%	0.61	0.48	0.38	0.28	0.18	0.10	0.07	0.04	0.03
FRCA	50%	0.63	0.57	0.53	0.27	0.21	0.16	0.09	0.05	0.02
FRCA	100%	0.65	0.60	0.57	0.34	0.26	0.20	0.10	0.07	0.05

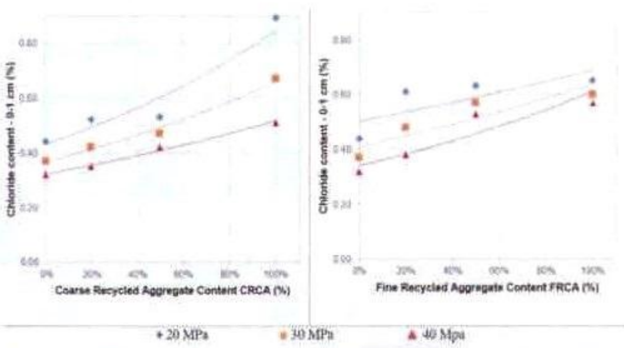


Fig. 5: Evolution of chloride content at a depth of 0 to 1 cm, with the amount of natural aggregate being replaced by CRCA and FRCA to achieve 20, 30, and 40 MPa at 28 days

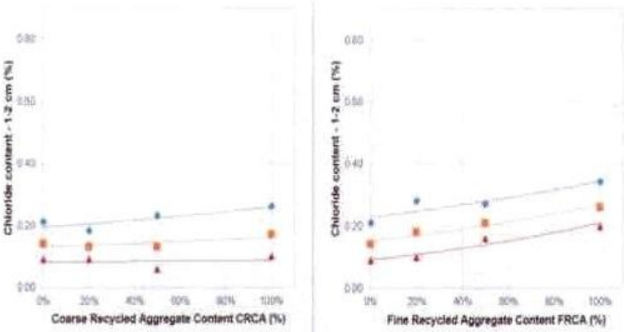


Fig. 6: Evolution of chloride content at a depth of 1 to 2 cm, with the amount of natural aggregate being replaced by CRCA and FRCA to achieve 20, 30, and 40 MPa at 28 days

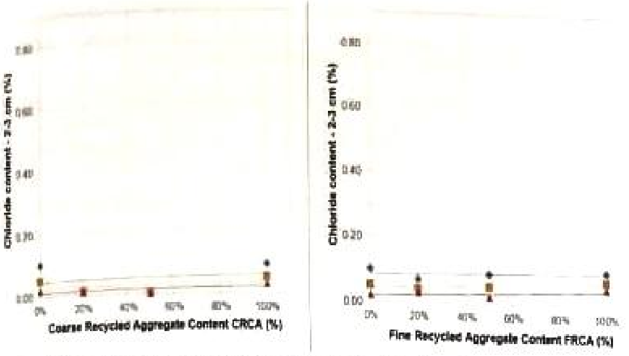


Fig. 7: Evolution of chloride content at a Depth of 2 to 3cm, with the amount of natural aggregate being replaced by CRCA and FRCA to achieve 20, 30, and 40 MPa at 28 days.

Comparison between result values and those established by National and International Standards.

Table 5 is synthesis produced from the reviewed literature, presenting the tolerance values established in diverse national and international standards and regulations.

The values shown in the trend curves in Figure5, Figure 6, and Figure 7are relative to the sample (concrete). If these values are transformed into their equivalent for cement, they would be approximately eight times higher.

Table 5
Standard limits for total chloride concentration [1]

Country	Standard	Maximum limit of Cl-for		Limit refers to
		Reinforced concrete	Prestressed concrete	
Brazil	NBR 6118	0.05%	---	Mix water
	NBR 7197	---	0.05%	
	NBR 9062	---	0.05%	
Spain	EH-88	0.40%	---	Cement
	EP-80	---	0.10%	
USA	ACI 222	≤ 0.20%	≤ 0.08%	Cement
	ACI201	≤ 0.20%	≤ 0.08%	
	ACI 318	≤ 0.30% Normal env. ≤ 0.16 Cl-env. ≤ 1.00% Dry env.	≤ 0.06%	
England	CP-110	≤ 0.35% 95%UR ≤ 0.50% 100% UR	≤ 0.06% 100%UR	Cement
Japan	JSCE SP-2	≤ 0.60 kg/m³	≤ 0.30 kg/m³	Concrete

Comparing the limits given in Table 5 with the values calculated in the mix design diagrams, it can be seen that none of the tested concretes meet the recommended conditions in the section nearest the surface, i.e. the range from 0 to 1 cm. At greater depths, in the 1 to 2cm and 2 to 3cm sections, the penetration of chlorides was below recommended limits, meeting the requirements of all standards.

In other words, by adopting 5 cm thick coating as prescribed in regulations for exposed concrete in marine environments, concrete made with recycled aggregates will perform similarly to the reference concrete made with natural aggregates, with regard to chloride penetration.

CONCLUSIONS

Under the conditions of this experiment, it was possible to conclude that: the use of recycled concrete aggregates to substitute natural aggregates, whether coarse or fine (CRCA, FRCA), independent of the amount substituted, reduces the resistivity of the concrete without, however, raising the probability of reinforcement corrosion above safe limits. Recycled aggregates, being more porous and less dense than natural aggregates, absorb more chloride in the surface layer; however, in deeper interior layers no significant difference was detected.The results obtained from this study demonstrate that, from the point of view of resistivity and chloride penetration, concretes made with recycled aggregates are viable in terms of durability and reinforcement protection.

The results of this study show that, with regard to the properties studied, it is possible to utilize recycled aggregate content higher than the 20% limit imposed by the majority of standards and regulations.

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