

Carbonation Rate and Reinforcing Steel Corrosion of Concretes with Recycled Concrete Aggregates and Supplementary Cementing Materials

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Because of the significant environmental impact that the concrete production causes, and as sustainability contribution for this industry; presently some improvements are being implemented in its durability and its components are being replaced for alternative recyclable materials. Concrete carbonation is one of the main causes of reinforcement electrochemical corrosion. Coarse Recycled Concrete Aggregates (RCA) and Supplementary Cementing Materials (SCM) such as fly ash and silica fume were used to produce durable and environmentally friendly concrete and for the evaluation of its carbonation depth and carbonation-induced reinforcement corrosion when it is exposed to accelerated conditions. The depth of carbonation was observed by spraying a phenolphthalein solution on the fresh broken concrete surface. The corrosion rates of steel embedded in these concretes have been measured by the lineal polarization resistance technique. The results indicate that to use RCA and SCM increase the carbonation depth and corrosion current density.

Keywords: Recycled aggregate concrete, Carbonation, Corrosion, Pozzolanic materials

1. INTRODUCTION

As a contributive strategy in the sustainability concrete industry, the durability improving of reinforced concrete structures is currently investigated, as well as the partial or total replacement of its

components for recycled materials. The most utilized alternative materials in concrete production are the Supplementary Cementing Material (SCM) such as silica fume (SF), fly ash (FA) and blast furnace slag as partial replacement of portland cement (PC); concrete with SCM has reported a good acceptance for its use [1-5] in some environments, emphasizing the favorable impact of the SCM in the performance of its resistance and durability, as well as in the environmental benefit involved. Regarding the aggregates, the Recycled Concrete Aggregates (RCA) is being used more frequently as a natural aggregates replacement and from ten years ago to now, the number of investigations about this topic has been increased significantly [6-15].

At present, the most important pathology in reinforced concrete structures is deterioration by electrochemical corrosion, caused by the chlorides penetration through concrete, as well as, by the carbonation of it.

The corrosion behavior induced by chlorides in reinforced concrete with RCA and SCM was studied in another works [1,16,17] and the basics principles of electrochemical corrosion of reinforced concrete is well known [18].

The CO₂ of the environment penetrates by capillary pore network of concrete and when is combined with humidity form carbonic acid, which reacts with calcium hydroxide (CH) turning it slowly into carbonates (of neutral pH); this phenomenon is known like carbonation. The carbonation of the concrete one modifies the propitious atmosphere (pH of 13) for the thermodynamic stability of the reinforcement steel and the chemical protection that the concrete one confers to him to the steel disappears beginning a process of generalized corrosion with the respective deterioration that this entails in reinforced concrete structures.

RCA (by adhered mortar) and SCM (by pozzolanic reaction) can provide increase and decrease, respectively in the alkaline reserve and porosity. Because this can cause concretes with different carbonation resistance, this research has the objective to analyze the concrete carbonation rate and corrosion behavior of reinforcing steel in order to know the RCA and SCM effect by accelerated CO₂ ingress.

Having the intention to evaluate the corrosion process in reinforced concrete specimens, electrochemical tests of linear polarization resistance (LPR) was carried out to determine the resistance to polarization (R_p) and corrosion current density (i_{corr}). As additional parameter, the compressive strength and total porosity were characterized.

2. EXPERIMENTAL METHODOLOGY

Four test specimens series with water-cementing material ratio of 0.48 were manufactured: a) reference specimens manufactured with 100% natural aggregate (NA) and 100% of Portland Cement (PC) Type I (ASTM C150), b) specimens carried out with 100% coarse RCA and 100% PC, c) specimen carried out with 100% coarse RCA and 30% FA as partial replacement of the PC, and finally, d) specimen manufactured with 100% coarse RCA and 10% SF as partial replacement of the PC. The characteristics and proportions of each series are shown in Table 1.

Table 1. Characteristics and proportion of the test mixtures (by 1m³ of concrete).

Materials (Kg)	Mixtures identification			
	Natural coarse and fine aggregate	Recycled coarse aggregate, natural sand and SCM		
	NA 100% PC	RCA 100% PC	RCA 30% FA	RCA 10% SF
Water	213.31	213.31	213.31	213.31
Gravel	994.55	870.58	870.58	870.58
Sand	766.17	915.35	915.35	915.35
Cement	444.44	444.44	311.11	400.00
SCM	0.000	0.000	133.33	44.44

2.1 Materials

The RCA has origin in the crushing of concrete test specimens, manufactured with natural aggregates, PC type I, relation water-cement of 0.50 and cured during a 28-day period to temperature and relative humidity (HR) of 23 ± 2 °C and 98 ± 1%, respectively. The natural aggregates proceed from crushed rock (coarse) and river sand (fine), obtained adequate particle size gradation according to the limits established by ASTM C33, some physical properties of these aggregates are shown in Table 2.

Table 2. Physical properties of the aggregates used in concrete mixtures

Type of aggregate	Relative density (g/cm ³)	Absorption (%)	Humidity (%)	Fineness module (%)	Maximum size (mm)
Recycled coarse	2.19	6.55	2.14	-	19
Natural coarse	2.50	0.44	0.28	-	19
Natural fine	2.43	4.08	6.66	2.73	4.76

Mexican FA low in calcium, Class F, according to norm ASTM C618, and American SF according to norm ASTM C1240, were employed as SCM. The physical-chemical properties of these materials are shown in Table 3.

Table 3. Physico-chemical properties of cementing materials.

Chemical composition (% of weight)								
Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	SO ₃	K ₂ O	Na ₂ O	MgO
CPC	19.94	4.40	2.97	63.50	3.08	0.42	0.12	-
FA	58.84	16.72	3.52	7.35	0.13	0.79	0.94	1.76
SF	95.22	0.08	2.37	0.26	0.11	0.56	0.30	0.24
Physical properties								
	Density (g/cm ³)		Specific surface, BET (m ² /kg)			Average size (μm)		
CPC	3.15		1400			15-25		
FA	2.35		1200			5-15		
SF	2.27		19600			0.1-0.2		

2.2 Compressive strength and Porosity

Compressive strength of each series was carried out in twelve cylindrical specimens ($h=30$ cm, $\Phi=15$ cm); according with ASTM C39 three specimens of each mixture were tested in compression at 28, 90 and 180 days of curing (23 ± 2 °C and $98 \pm 1\%$ of temperature and relative humidity, respectively). Passed 90 days of curing, total porosity of concretes studied was evaluated according ASTM C642.

2.3 Carbonation Rate

After a 90 days period of their preparation, the test specimens (150 x 150 x 500 cm prismatic beams) were placed in a chamber with constant parameters: temperature (28 ± 1 °C), relative humidity ($70 \pm 3\%$), CO₂ concentration ($6 \pm 0.1\%$) and pressure (14 psi). Periodically during six months, the carbonation rate was measured in agreement with phenofalein method on slides of 50 mm thickness. Twelve readings were taking as shown in Figure 1.

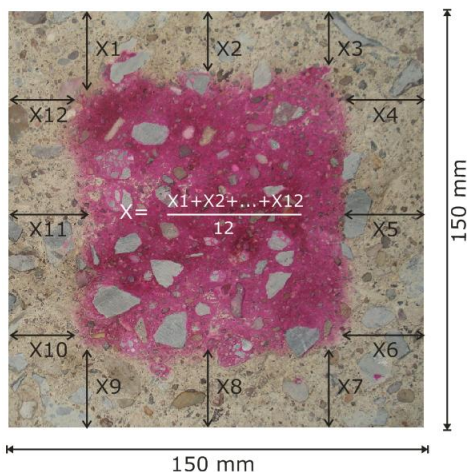


Figure 1. Readings location of carbonation depth (x)

2.4 Lineal Polarization Resistance

Having the purpose to evaluate R_p of the steel-concrete systems studied, three cylindrical test specimens were prepared ($h=30$ cm, $\Phi=15$ cm) for each mix shown in Table 1. Each test specimen was supplied with two embedded carbon steel bars UNS G10180 with 0.95 cm diameter, with an exposed area of 64 cm² and located at 4.5 cm from the outside. The steel bars were stripped and cleaned before their placement. After the 90-day of curing, the specimens were placed in the chamber along with prismatic beams. The (R_p) variation, correlative with the corrosion current density (i_{corr}) of the reinforcement was evaluated each week.

The evaluation of R_p was carried out by LPR in a potentiostat/galvanostat of ACM Instruments; the LPR test parameters were a swept potential of ± 20 mV at 10 mV/min. The steel bars worked as auxiliary and work electrode and a copper/copper sulfate was used as reference electrode. The experimental set up is shown in Figure 2.



Figure 2. Experimental scheme for testing LPR.

The resultant R_p was used to determine i_{corr} . Utilizing Equation 2 [19], where B is the Tafel constant, with recommended value [20-23] of 0.052 V for the reinforcement steel passive corrosion and 0.026 V for active corrosion;

$$i_{corr} = \frac{B}{R_p} \quad (2)$$

3. RESULTS AND DISCUSSION

3.1 Compressive strength and Porosity

The total porosity of mixtures NA 100% PC, RCA 100% PC, RCA 30% FA y RCA 10% SF was 22%, 26%, 23% y 17%, respectively. According to these results the use of RAC increased of

important way the concrete porosity, whereas to use SCM reduced the porosity, the same behavior also was observed in other investigations [4,24].

The compressive strength of four variables under study are shown in Table 5, in this one, it is possible to be stated the effect of the RCA and the SCM in the evolution of the compressive strength. The mixture that evaluates the effect of the RCA in the compressive strength (RCA 100% PC) developed strength of 26, 28 and 32 MPa to the 28, 90 and 180 days of curing respectively; these values, represent a loss of strength of 13, 15 and 10% respectively with respect to the control variable, which is coherent with other investigations [8,10,12-14]. Variable RCA 10% SF reported the greater value of compressive strength to 28, 90 and 180 days of curing (37, 41 and 43 MPa, respectively), which indicates that the use of 10% SF is translated in a gain of strength of 45, 44 and 35% more than the variable RCA 100% PC; in addition, are superiors to the obtained ones in the concrete variable of conventional concrete (NA 100% PC). As far as the FA use, mixture RCA 30% FA offered the lowest strength (17, 21 and 27 MPa), with losses of the 32, 25 and 15% with respect to the variable RCA 100% PC (28, 90 and 180 days of cured, respectively). Although the use of RCA and FA entails loss of compressive strength, the mixtures with these materials exceed to the 90 days the 20 MPa of compressive strength.

3.2 Carbonation Rate

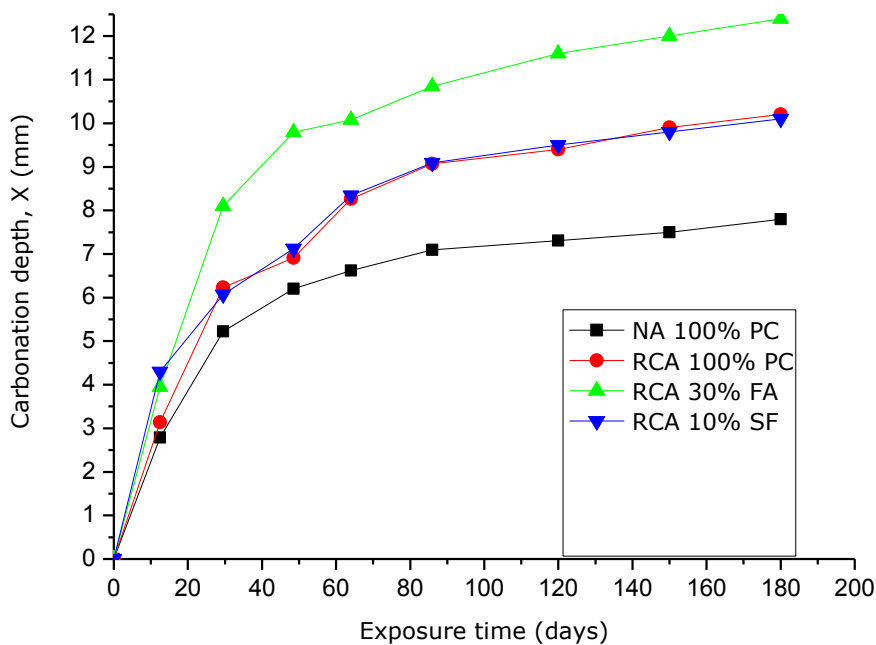


Figure 3. Carbonation depth variation as a function of exposure time

The results of carbonation depth in specimens throughout the exposure time are shown in Figure 3. It is possible to be observed in this figure that the concrete with 100% RCA and without MCS it exhibits majors carbonation depths that conventional concrete, smaller values than concrete with FA and the similar behavior that mixture with SF. The negative effect of 100% RCA in

carbonation depth is evident. The fact that concrete with SCM presents major carbonation depths can be attributed to the pozzolanic reaction of SCM, which consumes CH and consequently it reduces the alkalinity of concrete allowing a greater advance of carbonation front. Although the SF has greater reactivity than FA and therefore, during the pozzolanic reaction more CH is consumed and at greater speed, mixture RCA 10% SF presented minor advances of carbonation front than mixture RCA 30% FA due to porous system refinement that dominated in spite of the greater consumption of CH. The pore refinement and greater reactivity of SF could be corroborated by results of total porosity (section 3.1) and by scanning electron microscopy in cementing matrix as is shown in Figure 4.

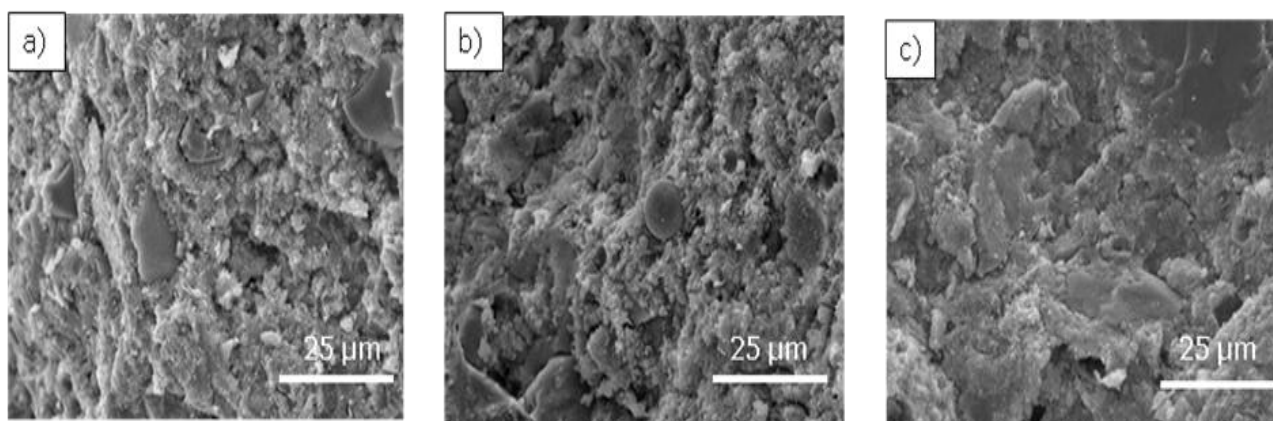


Figure 4. Microstructure of cementing matrix to 90 days of hydration: a) 100% PC, b) 70% PC – 30% FA, c) 90% PC – 10% SF.

In Figure 4 can be observed a dense microstructure in mixture with SF, whereas in mixture with FA heterogeneous matrix and spherical particles of FA can be observed, which indicates that the pozzolanic reaction in FA mixture is slower than SF mixture.

3.3 Lineal Polarization Resistance.

The corrosion behaviour of concrete-steel systems as a function of exposure time is represented in Figure 5.

In Figure 5 it is possible to observe that the use of 100% of RCA originates increments in the ionic conductivity of concrete and consequently major i_{corr} values, this is attributed to the porosity increment reported in section 3.1 by the presence of old and new interfacial transition zones that facilitate the ionic conduction. It is also observed that systems with SCM has the greater corrosion current density due to depletion of CH by pozzolanic reaction which means a decrement in pH levels in matrix.

The driving force (cell potential) in electrochemical process is a function of H^+ concentration (or pH) [26], which explains that mixtures with SCM have major level of corrosion current density.

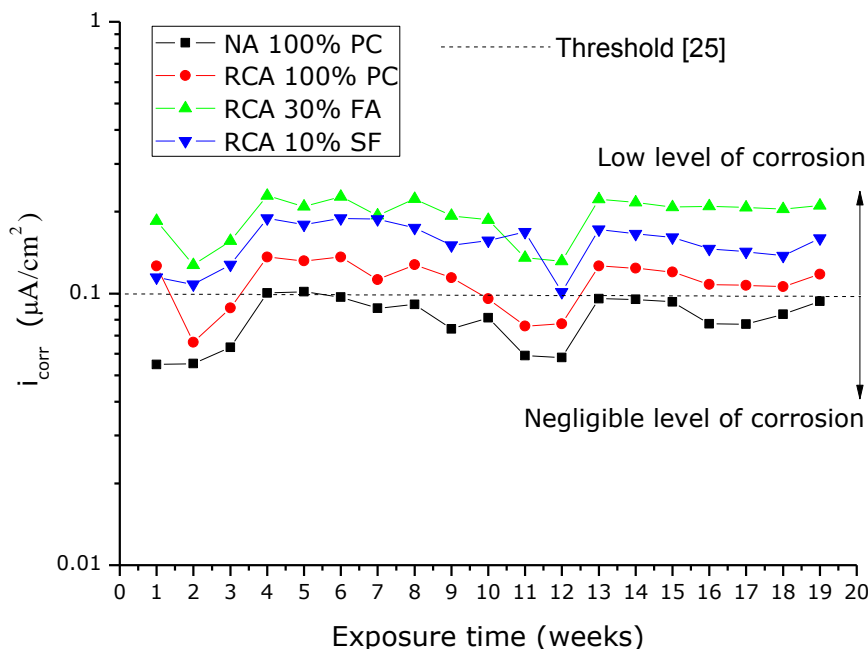


Figure 5. Variation of i_{corr} as a function of exposure time

4. CONCLUSIONS

To use 100% RCA increases in 20% the total porosity and decreases the compressive strength in 15% respect to reference mixture; nevertheless, the use of FA and SF in concretes with 100% of RCA decreases total porosity in 15% and 37%, respectively. To use SF increases compressive strength for specimens in 45% with respect to 100% RCA and 100% PC system. To use 100% RCA originates increments in the ionic conductivity of concrete and consequently major i_{corr} values. In spite of having minor porosity, the systems with SCM presented majors carbonation depths and corrosion current density indicating that the loss of alkalinity governed to pore refinement.

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