Mater. Res. Soc. Symp. Proc. Vol. 1488 © 2012 Materials Research Society
DOI: 10.1557/opl.2012.1549

Chloride Diffusion in Blended Cement Concrete Made with Quartzite Recycled Aggregate

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ABSTRACT

Using waste materials as aggregate for new concrete production is a growing tendency, because of several environmental problems. Recycled coarse aggregate (RCA) obtained from crushing waste concrete has lower density and greater absorption than natural aggregate, because of the higher porosity of the mortar attached to the RCA particles. Compressive strength level achieved in recycled concrete may be similar to that of conventional concrete. On the other hand, durable performance of recycled concrete is variable, and diverse evidence can be found in literature for different durability issues. In this paper, chloride ingress in conventional and recycled concrete, made with quartzite aggregate and blended Portland cement is evaluated when immersed in NaCl solution. Two strength levels (21 and 35 MPa) and two contents of RCA (25 and 75%), as substitute of natural quartzite aggregate, were considered. The chloride diffusion coefficient and the relationship between water-soluble chloride and bound chloride are analyzed.

INTRODUCTION

Using waste materials as aggregate for the production of concrete has gained importance because of the shortage of natural resources and environmental problems caused by storing waste from building demolition. Recycled coarse aggregate (RCA), obtained from crushing waste concrete, has different characteristics than those of natural coarse aggregate (NCA), such as greater absorption and lower density. These differences are attributed to the mortar from original concrete attached in RCA particles, which is more porous than the natural rock.

The use of RCA for new concrete production in replacement of NCA can modify some properties of concrete, especially those associated with durability. However, a compressive strength level similar to those of conventional concrete may be obtained, even with a percentage of RCA as high as 75% [1]. Regarding chloride penetration in particular, recycled concrete (100% RCA) having similar or slightly higher chloride penetration rate than that of equivalent conventional concrete (100% NCA) has been reported [2, 3], but differences between recycled and conventional concrete decreasing with increasing strength level have also been informed [4].

A fraction of the total chloride content that penetrates into concrete is bound by cement hydration products, and only some of it remains in the pore liquid (free chloride). This last fraction of chloride content is responsible for the depassivation of reinforcement.

Blended Portland cement (BPC) has lower clinker content than ordinary Portland cement. Limestone filler and slag may be included in BPC up to 35%. Limestone filler does not offer pozzolanic activity, but it increases early hydration rate. Slag is a pozzolanic latent hydraulic admixture additive that offers nucleation sites for early hydration and extra CSH formation at later ages, as well. Thus, the simultaneous use of these two admixtures is complementary. As regards the resistance to chloride ingress, BPC concrete is quite affected by curing treatment [5] and time [6].

Although cement type is the main factor influencing chloride binding capacity, hydration products in recycled aggregate may affect chloride binding capacity. In this study, recycled concrete of two strength levels (21 and 35 MPa) made with two contents of RCA (25 and 75%), obtained from crushed quartzite concrete, are evaluated. BPC, admixed with 18% of limestone filler and 12% of slag, was used. Concrete was exposed in immersion in NaCl 30g/l solution. Water-soluble and acid-soluble chloride profiles were measured for the determination of apparent chloride diffusion coefficients. From the relationship between water-soluble and acid-soluble chloride contents, chloride binding capacity is evaluated. The results from recycled concrete are compared to those obtained from conventional concrete.

EXPERIMENT

Blended Portland cement (CPC 40 according to IRAM 50000, similar to CEM II/B-M (L-S) 42.5 N according to EN 197-1), admixed with 18% of limestone filler and 12% of slag, was used. As fine aggregate, siliceous river sand was used (Fineness modulus: 2.30). Three types of coarse aggregate, nominal size 6-20mm, were used: Quartzite (Q) as NCA, and two RCAs (RQ21 and RQ35) obtained from crushing waste concrete made with Q aggregate with two strength levels (21 and 35MPa). A water-reducingerreducer admixture was used in recycled concrete, to keep similar workability level to that of conventional concrete and reduce the effect of the higher absorption of RCA.

Physical and chemical properties of BPC are presented in Table I. The properties of fine and coarse (natural and recycled) aggregates are presented in Table II. RQ aggregates present lower specific gravity and higher water absorption than Q, due to the mortar attached to the RCA particles. Q aggregate presents a non-despicable water absorption, as well. In the “Los Angeles” abrasion test, RQ had less abrasion loss than Q, which can be attributed to the petrographic characteristics of the natural sedimentary rock. With respect to the attached mortar, RQ21 had lower mortar content than RQ35, due to the higher mortar content lost in the crushing process. The mortar loss in the crushing process depends on the strength level of the original concrete [7].

Table I. Physical and chemical properties of BPC.

Specific surface (m^2/kg)			398		Density (g/cm^3)			3.03
Chemical composition (%)								
LOI	IR	SiO_2	CaO	Al_2O_3	Fe_2O_3	SO_3	MgO	Cl^-
3.0	2.7	19.0	60.95	7.37	3.88	1.87	0.95	0.011

Table II. Properties of fine and coarse aggregates.

Properties	Siliceous sand	Q	RQ21	RQ35
Obtained from concrete	---	---	Q21 *	Q35 *
Specific gravity (ssd)	2.63	2.48	2.35	2.37
Water absorption (%)	0.8	2.0	6.0	5.9
"Los Angeles" abrasion (%)	---	60	55	52
Mortar content (% by weight)	---	---	54	61
* Similar to conventional concrete from Table III.				

Two series of mixes with 21 and 35 MPa compressive strength levels (C21 and C35) were produced. The strength levels were adopted in order to obtain structural concrete of different qualities according to the Argentine Regulations [8]: a minimum strength class (C21), and a higher strength class (C35, usually established to meet durability requirements). A conventional concrete and two recycled concretes with 25 and 75% of the total volume of coarse aggregate constituted by RCA, were produced in each series. The lower percentage was adopted based on the maximum content of RCA indicated in several recommendations [9-11], whereas the higher percentage corresponds to the maximum value for which similar compressive strength to conventional concrete is obtained [1, 12]. Each RQ aggregate was used to produce recycled concrete with the same strength level to as that of the original concrete from which this recycled aggregate was obtained. The recycled aggregates were used in air-dry state.

Table III shows mix proportions and potential water/cement ratio (w/c) for each concrete, along with the values of slump and unit weight determined at the fresh state. Compressive strength (f'c), evaluated at the age of 28 days according to ASTM C39 [13], is presented as well.

Table III. Mix proportions (kg/m^3).

Strength level	C21			C35		
Concrete	Q21	RQ21-25	RQ21-75	Q35	RQ35-25	RQ35-75
Water	180	180	180	180	180	180
Cement	275	275	275	400	400	400
Sand	880	880	880	800	800	800
NCA/RCA	900/0	675/215	225/645	900/0	675/215	225/645
Water reducer	-	1.1	1.4	-	1.6	2.0
Potential w/c *	0.62	0.61	0.58	0.43	0.42	0.40
Slump (mm)	55	50	60	55	70	85
Unit weight (kg/m^3)	2280	2270	2265	2325	2315	2310
f'_c (28 days) (MPa)	25.9	33.2	32.2	41.7	53.8	42.6
* Calculated considering the water absorption of coarse aggregate at 30' [14].						

Three 150x300mm cylinders for compressive strength tests, and a prism of 75x150x250mm for chloride diffusion tests were cast with each concrete. All specimens were cured in a fog room (tTemperature: 23±2ºC; relative humidity: 95%) for 28 days.

To assess the ingress of chloride, concrete samples were placed in immersion in NaCl 30g/l solution. In order to allow unidirectional chloride ingress, waterproof chlorinated rubber paint was previously applied on the lateral faces of the prisms. After 140 days of exposure, transversal slices approximately 6mm wide were sawn and crushed to dust [15].

Water-soluble chloride contents were measured by titration according to the Mohr’s method [16], and the acid-soluble chloride contents were obtained following the method described at ASTM C1152 [17]. Apparent chloride diffusion coefficients (Dap) were determined by regressing data to the widespread solution to Fick's Second Law [18], Equation (1). Where c(x,t) is the concentration at the depth x at time t; c0 is the surface concentration; x is the depth from the surface; Dap is the diffusion coefficient; and t is time.

$$c(x,t) = c_0 \cdot \left(1 - erf \frac{x}{2\sqrt{Dap \cdot t}} \right) \tag{1}$$

RESULTS AND DISCUSSION

The profiles of water-soluble chloride obtained for concretes of C21 and C35 series are presented in Figures 1 and 2, respectively. It can be observed that the contents of water-soluble chloride at different depths for conventional concrete (Q21 and Q35) are slightly higher than those for recycled concretes. With respect to the acid-soluble chloride content, the corresponding profiles obtained for C21 and C35 series are presented in Figures 3 and 4, respectively. For each series, all mixes present similar profiles of acid-soluble chloride content.

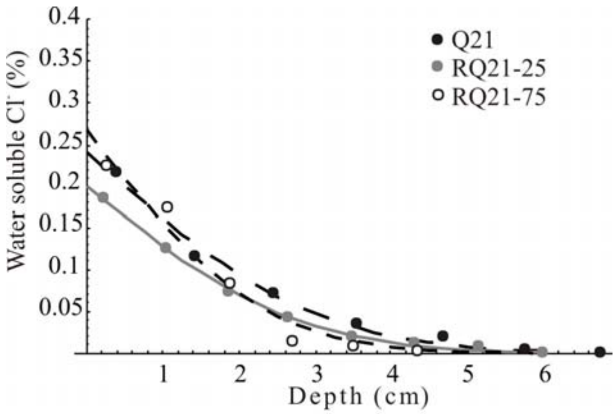

Figure 1. Profiles of water-soluble chloride for concretes of C21 series.

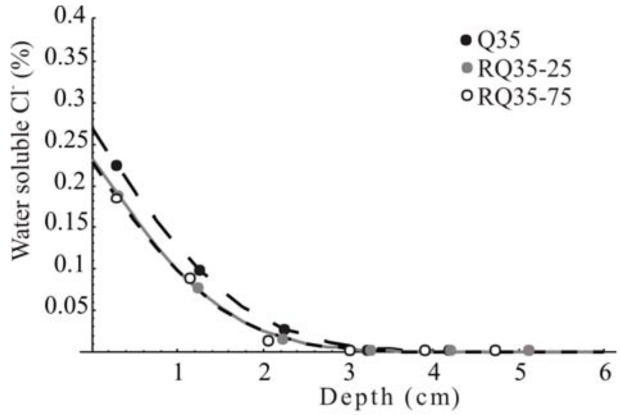

Figure 2. Profiles of water-soluble chloride for concretes of C35 series.

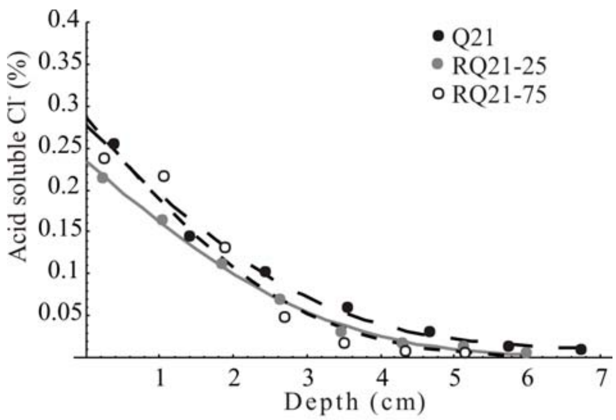

Figure 3. Profiles of acid-soluble chloride for concretes of C21 series.

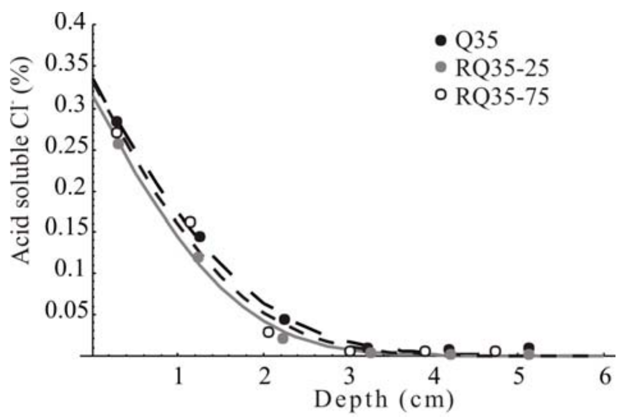

Figure 4. Profiles of acid-soluble chloride for concretes of C35 series.

The obtained Dap coefficients are presented in Table IV. Those values obtained for C21 are considered to indicate low durability for reinforced concrete in the marine environment, whereas the values for C35 are indicative of medium range durability [19]. These assumptions are valid for both conventional and recycled concrete. As well, Dap decreases with increasing content of RCA in all mixes, for both water-soluble and acid-soluble chloride contents. This fact can be attributed to the lower potential w/c of recycled concrete, because of the air-dry condition of recycled aggregate and the same mixing water content used in all mixes.

Moreover, from the coefficients presented in Table IV, it can be observed that for the C35 series, all mixes showed chloride diffusion coefficients coefficient lower than 10^{-11} m^2/s, even those made with 75% of RCA content. The indicated value for Dap is considered the limit for concrete with an adequate durable performance [19, 20]. As well, the w/c showed higher influence on chloride diffusivity than the content of RCA. Therefore, all mixes in the C21 series showed values for the chloride diffusion coefficient much higher than the limit mentioned above.

When considering the durability of reinforced concrete structures, the content of water-soluble chloride is of importance as it determines the chloride threshold content for reinforcement depassivation. For this reason, it is important to know the relationship between water-soluble chloride and bound chloride for the different mixes of each series. Figures 5 and 6 show these relationships for C21 and C35 series, respectively, and the corresponding trend line for each concrete.

It can be seen that, for a given content of water-soluble chloride, the content of bound chloride is higher with increasing content of RCA. The highest binding capacity of recycled concrete is attributed to the contribution of cement hydration products by the mortar attached to the particles of recycled aggregate.

Table IV. Chloride diffusion coefficients.

Strength level: C21	Dap (10^{-12} m^2/s)		Strength level: C35	Dap (10^{-12} m^2/s)	
	Water-soluble	Acid-soluble		Water-soluble	Acid-soluble
Q21	21.50	25.38	Q35	7.68	9.47
RQ21-25	17.35	23.94	RQ35-25	5.92	6.75
RQ21-75	12.21	19.00	RQ35-75	5.85	7.55

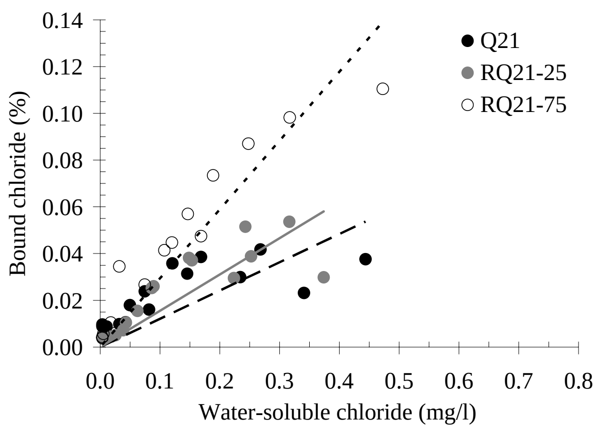

Figure 5. Water-soluble chloride vs. bound chloride for C21 concretes.

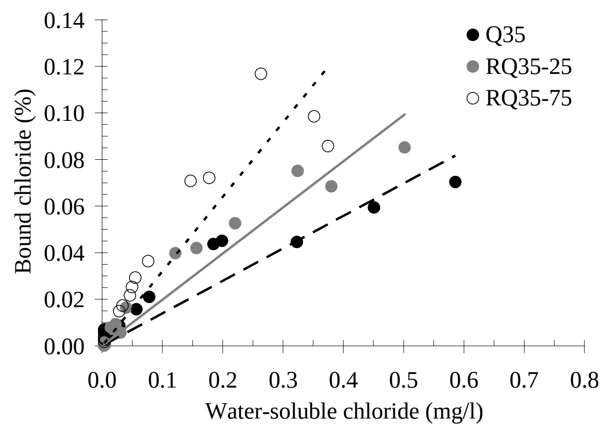

Figure 6. Water-soluble chloride vs. bound chloride for C35 concretes.

CONCLUSIONS

From the results obtained in the evaluation of chloride ingress in recycled concrete of two strength levels, and made employing 25 and 75% of quartzite RCA as substitute of natural quartzite aggregate, and the comparison to those obtained in conventional concrete of similar strength levels, the following conclusions arise:

The chloride ingress profiles of recycled concrete are similar to those of conventional concrete of the same strength level, even with a content of 75% recycled aggregate.

The potential water/cement ratio of concrete is determined by the absorption of aggregate, if it is not used in saturated condition and water reducers are available. In the case of recycled concrete, this factor affected the chloride diffusion coefficient, and it lowered it in comparison with conventional concrete made with natural aggregate having a lower absorption.

Recycled concrete offers higher chloride binding capacity than conventional concrete, due to the contribution of hydration products by the mortar attached to the particles of recycled aggregate.

The values for the chloride diffusion coefficients reveal that reinforced concrete made with blended Portland cement and recycled concrete is feasible to achieve intermediate durability in the marine environment. High durability may be expected for a higher strength level.

REFERENCES

1- C.J. Zega, A.A. Di Maio, *Bol. Tec.* (IMME), **45 (2)**, 1-11 (2007).
2- M.C. Limbachiya, T. Leelawat, R.K. Dhir, *Mater. Struct.*, **33**, 574-580 (2000).
3- N. Otsuki, S. Miyazato, W. Yodsudjai, *J. Mater. Civ. Eng.*, (ASCE), **15**, 443-451 (2003).
4- A. Gonçalves, A. Esteves, M. Vieira, in *International RILEM Conference on The use of recycled materials in building and structures*, (Barcelona, Spain), 554-562 (2004).
5- V.L. Taus, Y.A. Villagrán, A.A. Di Maio, in *Fifth ACI/CANMET International Conference on High-Performance Concrete Structures and Materials*, (Manaus, Brazil), 25-39, (2008).
6- Y.A. Villagrán Zaccardi, V.L. Taus, A.A. Di Maio, *ACI Mater. J.*, **107**, 593-601, (2010).
7- C.J. Zega, Y.A. Villagrán Zaccardi, A.A. Di Maio, *Mater. Struct.*, **43**, 195-202, (2010).
8- CIRSOC 201, *Reglamento Argentino de Estructuras de Hormigón*, (INTI, Buenos Aires, Argentina, 2005), 482p.
9- EHE*, Instrucción de Hormigón Estructural. Anejo 15, Recomendaciones para la utilización de hormigones reciclados,* (Ministerio de Fomento, Spain, 2008), 526-541.
10- RILEM Recommendation 121-DRG, *Mater. Struct.*, **27**, 557-559, (1994).
11- P. Grübl, M. Rühl, "German Committee for Reinforced Concrete (DafStb) – Code: Concrete with Recycled Aggregates," in *Proc. Int. Symposium Sustainable Construction: Use of Recycled Concrete Aggregates*, (London, UK), (1998). (Available in www.b-i-m.de)
12- A.A. Di Maio, C.J. Zega, L.P. Traversa, *J. ASTM Int.*, **2**, (2005), (www.astm.org)
13- ASTM C39, (ASTM International, West Conshohocken, PA, USA, 2003), 5p.
14- M.B. Leite, P.H. Pedrozo, D.C.C. Dal Molin, "Agregado reciclado para concreto: proposta de desenvolvimento de um método para determinação da taxa de absorção do material," in *Proc. 42º Congreso Brasilero del Hormigón* (IBRACON, Fortaleza, Brazil, 2000).
15- Y.A. Villagrán Z., C.J. Zega, A.A. Di Maio, *J. Mater. Civ. Eng.*, **20**, 449-455, (2008).
16- D.A. Skoog. D.M. West, F.J. Holler, S.R. Crouch, *Fundamentos de Química Analítica 8va. Edición*, (Thompson Learning, México D.F., Mexico, 2005), 1065p.
17- ASTM C1152, (ASTM International, West Conshohocken, PA, USA, 2003), 3p.
18- P.G. Shewmon, Diffusion in solids. McGraw-Hill Book Company Inc., (USA) (1963).
19- V. Baroghel-Bouny, in *Proceedings Third RILEM workshop on Testing and Modeling the Chloride Ingress into Concrete*, (Madrid, Spain, 2002), 137-163.
20- J.M. Frederiksen, H.E. Sørensen, A. Andersen, O. Klinghoffer, *HETEK, The effect of the w/c ratio on chloride transport into concrete - Immersion, migration and resistivity tests. The Road Directorate*, (Copenhagen, Denmark, 1997), 35p.