Influence of Natural Coarse Aggregate Type on the Transport Properties of Recycled Concrete

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Abstract: The use of recycled concrete represents an environmentally friendly solution for minimizing the impact of construction and demolition wastes. In many countries, the incorporation of recycled coarse aggregate (RCA) is a common practice because the maximum contents of RCA are usually limited to approximately 25% of the total coarse aggregate content. The incorporation of higher volumes of RCA is a field of discussion, primarily regarding the durable behavior of concrete. This study analyzes different transport properties of concretes with compressive strength of 20–50 MPa prepared with variable contents of RCA (0, 25, and 75%). Eight types of RCA were obtained from concretes incorporating four different natural coarse aggregates: granitic, basaltic, quartzitic crushed stones, and siliceous river gravel. Capillary absorption, water penetration, and chloride diffusion tests were conducted. The variation of transport properties with concrete compressive strength and the effect of RCA content on the variability of transport properties were analyzed. According to the results, the durable behavior of recycled concretes is different according to the transport mechanisms to which they are exposed and this behavior can match that of concretes made with natural coarse aggregates. **DOI:** 10.1061/(ASCE)MT.1943-5533.0000910. *© 2014 American Society of Civil Engineers.*

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Introduction

It is common practice to use compressive strength for characterizing concrete and estimating its potential durable behavior. In this sense, some guidelines such as the Argentine regulations [Centro de Investigación de los Reglamentos Nacionales de Seguridad para las Obras Civiles (CIRSOC) 201 2005] and the Spanish code [Instrucción de hormigón estructural (EHE) 2008] indicate minimum concrete strength levels according to the degree of aggressiveness of the exposure environment. Nevertheless, because many factors that affect transport properties in concrete do not necessarily modify the mechanical behavior in the same way, a concrete strength level does not necessarily ensure an adequate durable performance.

Coarse aggregate affects mortar–aggregate interfaces; adhesion and mechanical interlocking between the matrix and the aggregates are responsible for bond development. Additionally, there is a strong relationship between interface strength and failure behavior of concrete (Giaccio and Zerbino 1998). The paste volume, the porous structure of the matrix, and the quality of the interfaces control the transport of fluids in concrete. Gonilho Pereira et al. (2009) concluded that concrete durability properties are not affected by the aggregate mineralogy, but the informed results show absorption and capillarity coefficients 30% higher for calcareous aggregate concrete than for granite aggregate concrete, and the increases are in the order of 17 and 12% for basalt and marble aggregate concretes, respectively.

Different waste materials are usually employed in the construction industry. The advantages of obtaining coarse aggregates by recycling waste concrete have been recognized. Great economic and ecological benefits are involved and environmental pollution is reduced, as are nonrenewable natural resources (Lauritzen 2004; Melton 2004). Considering economic aspects, in many cases, the benefits are related to reductions in the transport costs of natural aggregates, because waste concrete can be reused in the same places where it is generated, i.e., large urban centers.

The most efficient applications of RC are obtained by using the coarse fraction of the recycled aggregate, because the fine fraction strongly increases water requirements [RILEM TC 121-DRG 1994; American Concrete Institute (ACI) Committee 555R-01 2002]. Recycled coarse aggregate (RCA) usually demonstrates particular characteristics compared to the natural aggregates, such as greater porosity and absorption and lower density and strength (Hansen and Narud 1983; Zega 2008; Padmini et al. 2009; Tabsh and Abdelfatah 2009). Rasheeduzzafar and Khan (1984) indicated that the matrix–aggregate bond strength in RCA is higher than or at least equal to that developed with natural coarse aggregate (NCA), which was verified by tests performed on small composed specimens (Casuccio et al. 2005). Previous studies showed that because the type of NCA affects the properties of conventional concrete, the coarse aggregate used in the original concrete may affect the properties of RCA more than the concrete strength level (Zega et al. 2010).

Regarding the effect of RCA on concrete mechanical properties, Hansen and Narud (1983) reported similar compressive strength in concretes with 100% of natural or recycled coarse aggregate. Other authors concluded that this property is not affected if less than 30% NCAs are replaced by RCA (Limbachiya et al. 2000; Gómez et al. 2001; Kwan et al. 2012). According to Di Maio et al. (2005), concretes incorporating up to 75% RCA can achieve compressive

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strength similar to that of concretes made with NCA. Most studies have shown that the use of RCA leads to higher reductions in stiffness (i.e., elastic modulus) than in strength (Hansen and Narud 1983; Zega 2008). Ajdukiewicz and Kliszczewicz (2002) indicated that the properties of original concrete strongly affect the mechanical properties of high-strength concrete made with RCA. Recycled concrete presents a decrease in the energy of fracture and in the size of the fracture zone (Casuccio et al. 2008) owing to improvements in interface strength and tensile/compressive strength ratio, and to reductions in stiffness, compared with concrete made with natural crushed stone as coarse aggregate. In summary, many studies have shown that, even for the same compressive strength level, other mechanical properties can vary between NCA and RCA concretes, primarily for high contents of RCA.

Concerning the durable behavior of RC, Limbachiya et al. (2000) concluded that concretes incorporating up to 30% of RCA have permeation properties [initial surface absorption (ISAT) and air permeability] similar to those of natural aggregate concretes. They also indicated that other properties, such as chloride penetration depth, chloride-induced corrosion, and freeze/thaw resistance, are similar in both types of concretes, even for those made with 100% RCA. Gonçalves et al. (2004) evaluated oxygen permeability, capillary absorption, and chloride diffusion, indicating that the differences between concretes incorporating recycled (100% RCA) and natural coarse aggregates (100% NCA) decrease with increased concrete strengths; these parameters are always higher in RC. On the other hand, Otsuki et al. (2003) concluded that the chloride penetration and carbonation depth of concretes with 100% RCA are slightly higher than in the reference concrete (100% NCA) with equal water/cement (w/c) ratio. Other authors indicated that concrete with 20% RCA presented the lowest water absorptions, and that the best performance of RC exposed to accelerated carbonation was obtained when between 20 and 50% RCA was used (Levy and Helene 2004). Thomas et al. (2013) found that the carbonation rate and the water penetration depth increase with the content of RCA and the w/c ratio. Kou and Poon (2012) concluded that the resistance to chloride ion penetration, the absorption, and the carbonation depth increase with increased contents of RCA. However, the durability properties of RC can be improved by the use of fly ash, as either replacement or addition of cement (Kou and Poon 2012). In brief, with respect to the durability of RC, a high variability in the results and conclusions appears when RCAs are used as a substitute for natural aggregates.

The objective of this study is to analyze the durability properties in concretes of different strength levels incorporating different types of RCAs. Concretes with w/c ratios of 0.45 and 0.65, prepared with different contents of RCA (0, 25, and 75%), have been studied. With the aim of evaluating different transport mechanisms, capillary absorption, water penetration under pressure, and chloride diffusion tests were performed. The effects of the type and content of RCAs on the variability of the durability properties of concrete are discussed.

Experimental Program

Materials and Mixtures

To obtain structural concretes of different qualities according to the Argentine regulations [Centro de Investigación de los Reglamentos Nacionales de Seguridad para las Obras Civiles (CIRSOC) 201 2005], two series of concrete with well-differentiated strength levels were made, adopting w/c ratios of 0.45 and 0.65. Concrete series with w/c ratio of 0.65 correspond to the lower (L) strength level indicated in the cited regulation, whereas those with w/c ratio of 0.45 are usually specified to meet durability requirements. In this paper, concretes with w/c ratio of 0.45 are identified as the higher (H) strength level.

Four coarse aggregates usually employed in the central region of Argentina were selected, with different petrographic, physical, mechanical, and interfacial properties. They include three crushed stones obtained from diverse rocks: granite (G), basalt (B) and quartzite (Q), and one siliceous river gravel (S). For the purpose of the study, these are all referred to as NCA. The characteristics and some properties of these four aggregates are presented in Table 1. Aggregate G displays an irregular shape, rough texture, and low absorption; the properties of Aggregate B are quite similar to those of Aggregate G, with greater water absorption and density. Aggregate Q also displays an irregular shape and rough texture, but it has the highest water absorption of the four natural aggregates. Finally, Aggregate S is composed of strong particles with very smooth surfaces and low porosity. Aggregates G and B have similar void contents, which slightly decreases in Aggregate Q, and Aggregate S has the lowest value, which is attributable to differences in the particle shape of each natural aggregate.

Eight RCAs were obtained by crushing concretes of Series H and L made with each type of NCA; the fine fraction (pass number 4.75 mm) was discarded. A comparative analysis of the properties of both RCA and NCA was performed in a previous paper (Zega et al. 2010). Table 2 summarizes the characteristics of RCA. The maximum size and fineness modulus of RCA are similar to those of the respective NCAs, water absorption is higher in RCA than in NCA because of the presence of attached mortar; Aggregates RQ present the highest absorption. Considering the Los Angeles abrasion test results, Aggregates RG, RB, and RS display higher weight losses than the respective NCAs, as expected, but the weight loss is lower in Aggregates RQ than in Aggregate Q. The flakiness index of Aggregates RG, RQ, and RB is lower than in the respective NCAs because of the process for obtaining these natural aggregates.

Four conventional concretes (100% NCA) as reference mixtures and eight recycled concretes replacing 25 and 75% by volume of NCA with the corresponding RCA were prepared in each series (H and L). The lower percentage of replacement was adopted based on the maximum content of recycled aggregate indicated in several recommendations [Instrucción de hormigón estructural (EHE) 2008; RILEM TC 121-DRG 1994; Grübl and Rühl 1998].

Table 1. Natural Coarse Aggregates

NCA	Shape	Surface texture	Grain size	Maximum size (mm)	Fineness modulus	Specific gravity	Water absorption 24 h (%)	Los Angeles abrasion (%)	Unit weight (kg/m^3)	Flakiness index (%)	Elongated index (%)	Voids (%)
Granite	Irregular	Crystalline	Medium	19	6.72	2.72	0.3	25	1,410	19	27	48
Quartzite	Irregular	Crystalline	Medium	19	6.73	2.48	2.0	60	1,310	25	22	46
Basalt	Irregular	Rough	Fine	19	6.68	3.03	0.8	9	1,530	27	29	49
Siliceous river gravel	Rounded	Smooth	Fine	19	6.58	2.60	0.5	19	1,580	10	21	38

Table 2. Recycled Coarse Aggregates

RCA	Shape	Surface texture	Maximum size (mm)	Fineness modulus	Specific gravity	Water absorption 24 h (%)	Los Angeles abrasion (%)	Unit weight (kg/m^3)	Flakiness index (%)	Elongated index (%)	Voids (%)	Mortar content (% by weight)
RG-H	Irregular	Rough	19	6.69	2.52	4.0	35	1,220	13	23	49	39
RQ-H	Irregular	Rough	19	6.71	2.37	5.9	52	1,100	15	37	51	61
RB-H	Irregular	Rough	19	6.71	2.66	3.9	25	1,260	11	25	51	41
RS-H	Irregular	Rough	19	6.57	2.45	3.9	32	1,190	11	31	50	44
RG-L	Irregular	Rough	19	6.69	2.51	4.1	37	1,190	10	28	51	35
RQ-L	Irregular	Rough	19	6.67	2.35	6.0	55	1,140	13	16	49	54
RB-L	Irregular	Rough	19	6.61	2.65	4.5	30	1,290	10	20	49	33
RS-L	Irregular	Rough	19	6.57	2.44	4.4	37	1,210	10	22	48	38

Note: RG-H = RCA obtained from class H concrete made with granitic aggregate; RG-L = RCA obtained from class L concrete made with granitic aggregate. RQ-H = RCA obtained from class H concrete made with quartzitic aggregate; RQ-L = RCA obtained from class L concrete made with quartzitic aggregate. RB-H = RCA obtained from class H concrete made with basaltic aggregate; RB-L = RCA obtained from class L concrete made with basaltic aggregate. RS-H = RCA obtained from class H concrete made with siliceous aggregate; RS-L = RCA obtained from class L concrete made with siliceous aggregate.

The higher percentage corresponds to the maximum value observed in previous studies in which RC achieved compressive strengths similar to those of concretes prepared with NCA (Di Maio et al. 2005; Zega and Di Maio 2007).

Table 3 shows the concrete mixture proportions. Both series include three sets of concretes for each NCA. The mixtures are identified in accordance with the type of coarse aggregate and the percentage of RCA replacement. Blended portland cement (ASTM Type I) and siliceous river sand (fineness modulus: 2.30; specific gravity: 2.63) were used. As indicated previously, w/c ratios of 0.45 and 0.65 were adopted for Series H and L, respectively, and the water requirement was adjusted in accordance with the type of NCA. With the aim of comparing the effect of aggregate type on concrete transport properties, the coarse aggregate volumes were kept constant. In addition, and to compensate for the differences in water absorption between NCA and RCA, a water-reducing admixture was used in RC to obtain similar slump levels (80 ± 20 mm) in each set of concretes, minimizing variations in the characteristics of the cement paste. However, because RCAs were used in air-dry condition, the potential w/c ratios are slightly lower in RC than in conventional concretes. The potential w/c ratio considering the water absorption of RCA after 30 min is also indicated in Table 3.

With each concrete, three cubes with sides of 200 mm for the water penetration test, five 100 × 200 mm cylinders for the capillary absorption test, a 75 × 150 × 250 mm prism to evaluate the chloride diffusion coefficient, and three 150 × 300 mm cylinders for the compressive strength test were cast. More information is presented in Table 4. All specimens were cured in a fog room (temperature: 23 ± 2°C; relative humidity: 95 ± 5%) for 28 days.

Table 3. Concrete Mixture Proportions

Series	Concrete	Materials (kg/m^3) Water	Cement	Sand	NCA	RCA	Admixture	Potential w/c[a]
H	G-H	165	370	855	1,010	—	—	0.45
	RG-H-25				755	235	1.1	0.43
	RG-H-75				245	700	1.9	0.40
	B-H	165	370	855	1,125	—	—	0.45
	RB-H-25				840	245	1.1	0.43
	RB-H-75				280	740	1.9	0.40
	Q-H	180	400	800	900	—	—	0.45
	RQ-H-25				675	215	1.6	0.43
	RQ-H-75				225	645	2.0	0.40
	S-H	160	360	870	955	—	—	0.45
	RS-H-25				725	225	1.0	0.43
	RS-H-75				240	680	1.8	0.40
L	G-L	165	255	950	1,010	—	—	0.65
	RG-L-25				755	235	0.8	0.63
	RG-L-75				245	700	1.3	0.58
	B-L	165	255	950	1,125	—	—	0.65
	RB-L-25				840	245	0.8	0.62
	RB-L-75				280	740	1.3	0.57
	Q-L	180	275	880	900	—	—	0.65
	RQ-L-25				675	215	1.1	0.63
	RQ-L-75				225	645	1.4	0.57
	S-L	160	245	960	955	—	—	0.65
	RS-L-25				725	225	0.7	0.63
	RS-L-75				240	680	1.2	0.58

[a]Calculated considering the water absorption of coarse aggregate at 30 in. [data from Leite et al. (2000)].

Testing Methods

The capillary absorption test is particularly sensitive to the size of the connected pores. Tests were conducted according to Instituto Argentino de Normalización y Certificación (IRAM) 1871 (2004). The method consists of recording, at fixed intervals, the mass increment by capillary suction of a specimen with one face in contact with water. Five cylindrical specimens, 100 × 200 mm, were molded and a 100 × 50 mm slice was sawn from 30 mm from the bottom of each specimen. To avoid moisture absorption through the lateral surface of the specimen (not considered in the calculations) and to keep the test area constant (circular face exposed to water), the lateral surface was sealed with waterproof paint. The specimen was dried in an oven at 50 ± 2.5°C until constant mass was achieved, that is, until the difference between two consecutive weighings made at 24 ± 1 h intervals was lower than 0.1% of the last measurement. Finally, the specimens were placed on sharp supports into a hermetically closed container at 20 ± 2°C, with a water

Table 4. Experimental Design Program

Test	Type and size of specimens	Number of specimens tested for each concrete	Total number of tests
Compressive strength	150 × 300 mm cylinders	3	72
Water penetration	200 mm side cubes	3	72
Capillary absorption	100 × 50 mm sliced cylinders	5	120
Chloride diffusion	75 × 150 × 250 mm prism	1	24

height of 3 ± 1 mm on the absorption face; these conditions were maintained during the course of the test.

The amount of absorbed water was the mass gain at 1/2, 1, 2, 3, 4, 5, 6, 24, and 48 h and at subsequent 24 ± 1 h intervals, until the mass gain of the specimen was lower than 0.1% between two consecutive determinations. Mass was measured to the nearest 0.1 g. Each weighing operation was completed in 30 s, and both the time and the mass were recorded. The capillary suction rate (sorptivity) is calculated as the slope of the straight line obtained by linear regression of the experimental determinations, by plotting the cumulative mass of water absorbed by unit area of wetted cross section, in g/m^2, versus the exposure time, in $s^{1/2}$.

The fluid movement through the saturated pore structure of concrete under pressure was evaluated by the water penetration test. The determinations were conducted according to BS EN 12390-8 (British Standards Institution 2009) on cubes with 200 mm sides. The pressure cycle consists of 0.1 MPa for 48 h, 0.3 MPa during the following 24 h, and 0.7 MPa for 24 h. After that, the specimens are broken by splitting and the humid profile is recorded to obtain the average depth of water penetration.

Chloride penetration is of particular interest when considering the durability of RC. Prisms of 75 × 150 × 250 mm were placed in an aqueous solution of sodium chloride at a concentration of 30% (weight/volume). To allow unidirectional chloride ingress, three layers of waterproof chlorinated rubber paint were previously applied on the lateral faces of the prisms. After 140 days of exposure, transversal slices 6 mm wide were sawn (Villagrán-Zaccardi et al. 2008); the water-soluble chloride contents were measured by titration according to Mohr's method (Skoog et al. 2005), and the apparent chloride diffusion coefficient was determined by applying the solution to Fick's Second Law (Shewmon 1963).

As a reference parameter, the compressive strength was determined in each concrete at the age of 28 days, according to ASTM C-39 (2003).

Analysis of Results

To analyze the effect of RCA, Fig. 1 shows the compressive strength of each set of concretes for Series H and L. RCs have compressive strengths comparable to those of conventional concretes. There is an increase in strength in concretes incorporating 25% RCA, which is more evident in Series L, and concretes with 75% RCA have practically the same strength level. This is attributed to the combined effects of a slight reduction in the w/c ratio in RC owing to the absorption of recycled aggregate particles, which improves the quality of mortar matrix–RCA interfaces, and the increased number of weak particles of RCA. The latter effect was probably more significant in concrete incorporating 75% RCA. Regarding the effect of mortar-aggregate bond strength, the compressive strength increases as the RCA content increases in concretes incorporating river gravel (S). The particles of Aggregate S are rounded with a very smooth surface texture, whereas RS particles are irregular with a rough surface texture.

Thus, considering the preceding observations, the concretes of each series are representative of the same strength level. The influence of the type of coarse aggregate on the transport properties of concrete is analyzed in the following.

Capillary Absorption

Fig. 2 compares the results of sorptivity measured in each series. The dotted line indicates the limit established by the Argentine regulation for concretes made with NCA. The highest sorptivity obtained in conventional concretes corresponds to those made with Aggregates Q and S. The superior porosity of Aggregate Q and the poor quality of the Aggregate S–mortar interfaces justify this behavior.

Considering the effect of RCA, concretes made with Aggregates G, B, and Q show sorptivity increments as the percentage of RCA increases, which is attributed to the higher porosity of RCA

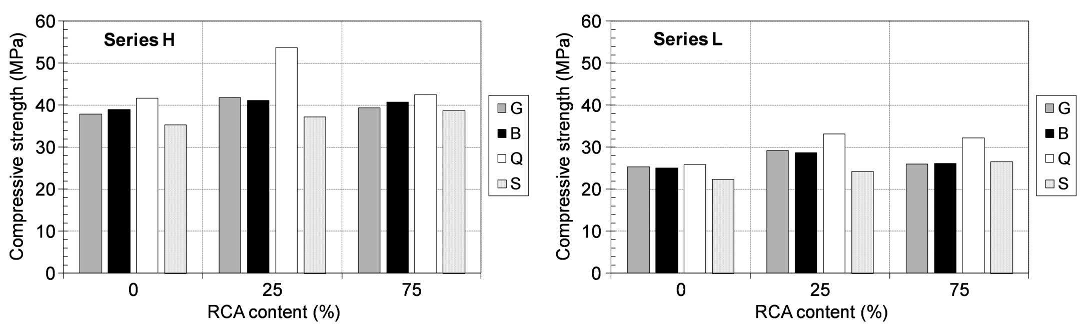

Fig. 1. Compressive strength of concretes incorporating different types and contents of RCA

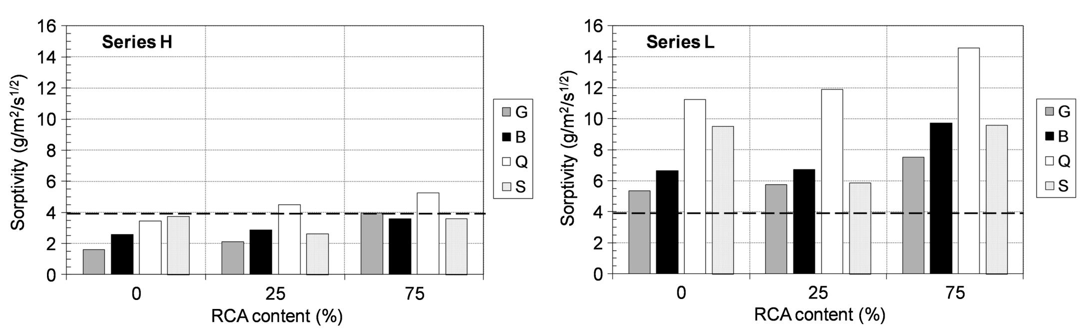

Fig. 2. Sorptivity values obtained from capillary suction tests

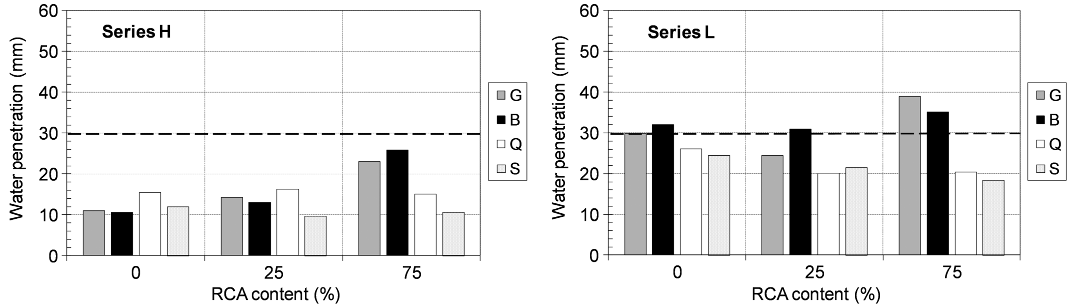

Fig. 3. Water penetration test results

particles. In concretes of Series H, the increments in sorptivity are 30 and 140% (G), 11 and 40% (B), and 30 and 50% (Q) for concretes with 25 and 75% RCA, respectively. On the contrary, recycled concretes with Aggregate S present lower sorptivity than conventional concretes, for both concrete series. This can be associated with the modifications at the aggregate–mortar interfaces.

Finally, Fig. 2 shows that concretes of Series H achieved sorptivity values lower than 4 $g/m^2/s^{1/2}$, with the exception of concretes incorporating Aggregate RQ. The Argentine regulation [Centro de Investigación de los Reglamentos Nacionales de Seguridad para las Obras Civiles (CIRSOC) 201 2005] establishes this limit as a durability requirement for structural concretes with natural aggregates. The superior values of sorptivity reached in RQ concretes are justified by the higher water absorption (6%) of these recycled aggregates (Table 2); increases are also displayed in sorptivity in concretes containing 75% RCA. As expected, concretes of Series L show sorptivity values higher than the indicated limit; the effects of the type of NCA and RCA contents are evident.

Water Penetration under Pressure

Fig. 3 shows the results of water penetration tests. The dotted line indicates the limit established by the Argentine regulation for concretes made with NCA. All concretes of Series H present average depths of water penetration lower than 30 mm, even for the higher RCA contents, which is the limit indicated by the Argentine regulation [Centro de Investigación de los Reglamentos Nacionales de Seguridad para las Obras Civiles (CIRSOC) 201 2005] as a durability requirement for concretes used in water retaining structures. The regulations of other countries, such as Spain [Instrucción de hormigón estructural (EHE) 2008], also establish this limit as a condition of durability. Penetration depths increased in Series L, as expected; nevertheless, some concretes meet the limit, although they were not designed to meet durability requirements.

When RC is compared with conventional concretes, the behavior differs with the type and content of coarse aggregate. In Series H, the depths of water penetration increases with the RCA content in concretes G and B; these increments were 29 and 110% (G), and 23 and 145% (B) in concretes prepared with 25 and 75% RCA, respectively. When concretes with Q are analyzed, water penetration depths are similar (differences ±5%) in Series H, whereas in Series L, the depths in RC are 22% lower than in conventional concretes. Regarding concretes with S, the values are similar in Series H, whereas in Series L, the penetration depths decrease as the content of RCA increases.

Chloride Diffusion

Fig. 4 presents the apparent water soluble chloride diffusion coefficients measured on conventional and recycled concretes. In contrast with the case of capillary absorption and water penetration tests, the Argentine regulation does not specify a limit for the chloride diffusion coefficient to define the durable behavior of concretes. Nevertheless, concretes with a diffusion coefficient lower than 10.10^{-12} m^2/s (dotted line in Fig. 4) should present adequate durable behavior (Frederiksen et al. 1997; Baroghel-Bouny 2002).

For both series, the performance of concretes varies with the type of coarse aggregate. In Series H, the diffusion coefficient of concretes with Aggregates G and B increases with the RCA content. These increments were close to 64 and 134% (G), and 9 and 113% (B) in concretes incorporating 25 and 75% RCA, respectively. Based on the measurements of water absorption (Tables 1 and 2), this behavior is associated with the greater porosity of these RCAs when compared with the corresponding natural concretes. On the contrary, the diffusion coefficients decrease between 20 and 45% in RC incorporating Aggregates RQ and RS. The better response of RQ concretes is primarily attributed to a greater chloride binding capacity owing to the higher mortar content in RQ aggregates (Table 2). In the case of RS concretes, the improved performance is associated with the quality of interfaces, because the matrix–aggregate bond strength strongly increases in RS particles compared with those of Aggregate S.

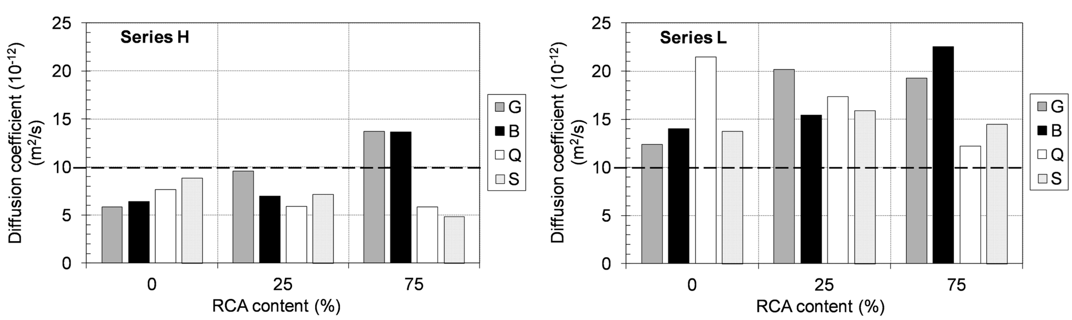

Fig. 4. Apparent water soluble chloride diffusion coefficients

As shown in Fig. 4, and according to the literature (Frederiksen et al. 1997; Baroghel-Bouny 2002), with the exceptions of RG-H-75 and RB-H-75, satisfactory durable behavior should be expected for most concretes of Series H.

Discussion

Variation of Transport Properties with Concrete Compressive Strength

Many times, the compressive strength is employed as a reference of concrete characteristics, including its durable behavior. In this sense, requirements have been proposed for the minimum strength for concretes with NCA, but this is not the case for RC. The relationship between the compressive strength and the durable parameters of the concretes under evaluation, which were prepared with different types and contents of recycled coarse aggregate, is discussed in the following.

Fig. 5 shows the relationship between sorptivity and compressive strength, considering all concretes in the study. The dotted line indicates the limit established by the Argentine regulations for concretes made with NCA. As shown, concretes with NCA and RCA follow a similar behavior, showing a decrease in sorptivity as compressive strength increases. This behavior is consistent with that indicated by Gonçalves et al. (2004), in which capillary absorption of 100% RCA concretes decreases as the compressive strength level increases. Regarding the effect of the type of coarse aggregate, the sorptivity increases in concretes with Aggregates Q and RQ, which must be associated with the porosity of the rock.

The variation in the water penetration depth with the compressive strength is presented in Fig. 6. The dotted line indicates the limit established by the Argentina regulations for concretes with

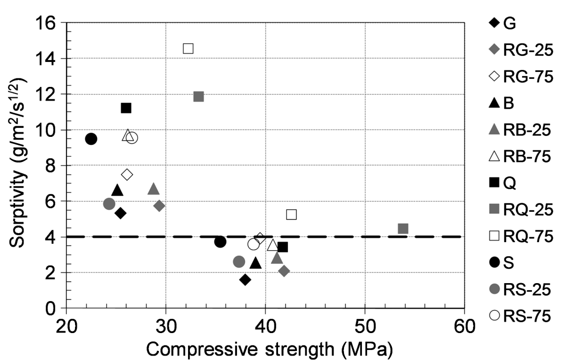

Fig. 5. Variation of the sorptivity with the compressive strength

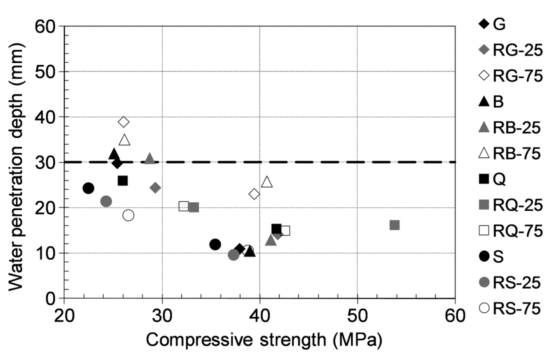

Fig. 6. Variation of the water penetration with the compressive strength

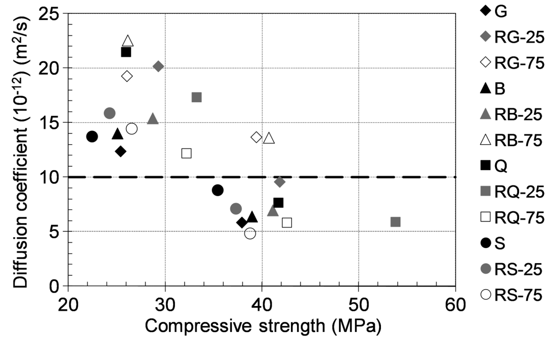

Fig. 7. Variation of the chloride diffusion coefficient with the compressive strength

NCA. As with the sorptivity, the increase in compressive strength diminishes the water penetration depth, independently of the type and content of RCA. Thomas et al. (2013) found similar results, showing higher water penetration as the w/c ratio increases. Concretes incorporating 75% of Aggregates RG and RB show the greatest penetration depths. The effect of compressive strength on the decrease of penetration depth is less significant than that in the case of the sorptivity.

Finally, Fig. 7 shows the relationship between the compressive strength and the chloride diffusion coefficient. The dotted line indicates the limit for concretes that should present adequate durable behavior. As in previous cases, the diffusion coefficients decrease as concrete strength increases, with both NCA and RCA concretes showing the same tendency. This behavior is coincident with that shown by Gonçalves et al. (2004). Although the diffusion coefficients tend to be higher in concretes with RCA, it is not possible to find a clear effect of the RCA content.

Effect of the Content of RCA on the Variability of Transport Properties in Concrete

To discuss the effects of RCA on the durability of concrete, it is interesting to analyze the variability of the transport properties in concretes of similar strength prepared with different types and contents of coarse aggregates. Figs. 8–10 compare the ranges of variation of each property for 0, 25, and 75% RCA including all types of NCA.

Considering capillary suction tests (Fig. 8), the range of variation for the sorptivity results in concretes with RCA is similar to that of concretes with 100% NCA. As mentioned previously, the sorptivity tends to increase as RCA increases; in both series, concretes with 25% RCA achieve values similar to those of reference concretes, whereas in concretes with 75% RCA, average values increase by nearly 40%. Nevertheless, in each series, the ranges of variation of the parameters are superimposed; thus, it is possible to obtain similar values of sorptivity, even incorporating RCA. The results of sorptivity agree with those obtained by Limbachiya et al. (2000), who found an increase in the permeability of concretes incorporating RCA in proportions greater than 30%.

Fig. 9 compares the results of water penetration tests. In both series, the variation range in 100% NCA concretes is similar to that of concretes prepared with 25% RCA, in both cases incorporating different types of coarse aggregates. The range of variation increases in concretes with 75% RCA. However, the ranges are superimposed and there are no great differences in the averages. According to Thomas et al. (2013), the depths of water penetration of concretes with 20% RCA are similar to those of 100% NCA concretes, increasing for higher contents of recycled aggregate.

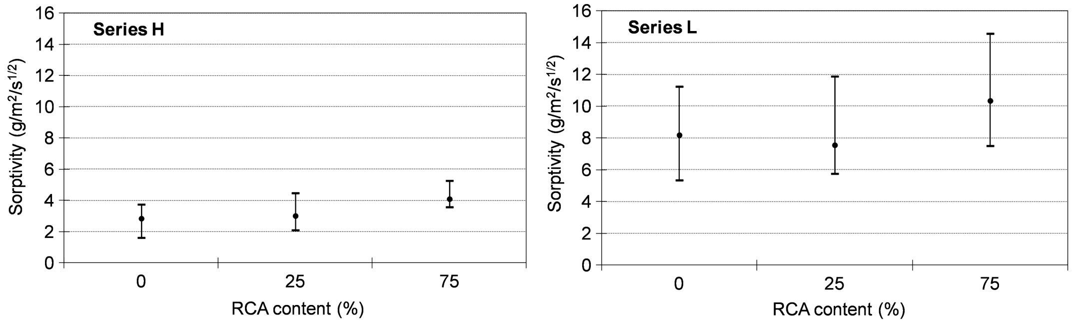

Fig. 8. Variability of the sorptivity in concretes with different types and contents of NCA and RCA

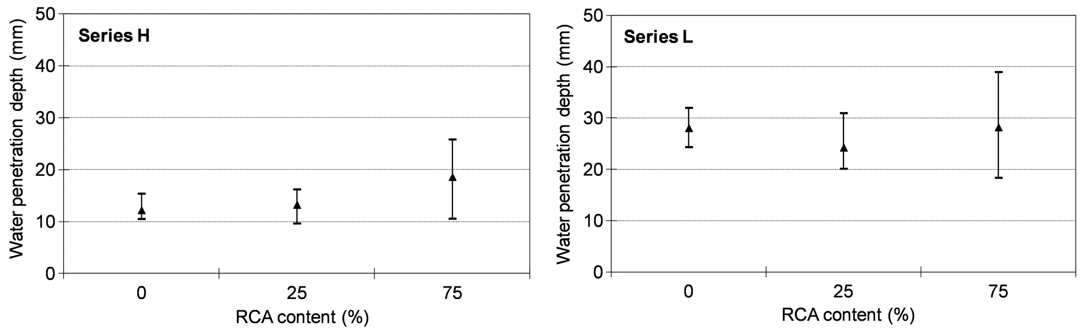

Fig. 9. Variability of the water penetration in concretes with different types and contents of NCA and RCA

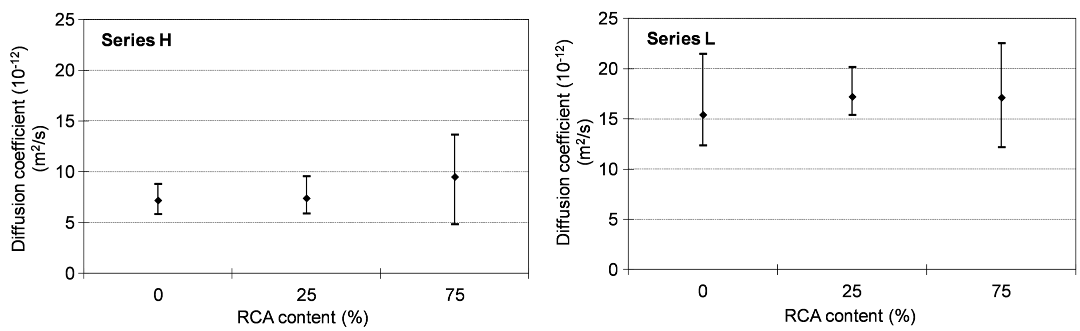

Fig. 10. Variability of the chloride diffusion coefficient in concretes with different types and contents of NCA and RCA

Similar behavior can be observed from the measurements of chloride diffusion coefficients (Fig. 10): the same range of variation for concretes with 100% NCA and concretes with 25% RCA, and a tendency to increase the variability and the average values in concretes incorporating 75% RCA. Similarly, Kou and Poon (2012) indicated that chloride penetration increases with the content of RCA, and when fly ash is used as complementary cementitious material, chloride penetration shows a significant decrease for both conventional and recycled concretes. On the contrary, Limbachiya et al. (2000) indicated that for 100% RCA concretes, the chloride penetration depth is similar to that of concrete made with 100% of NCA.

In summary, in concretes with similar compressive strengths, the effect of incorporating RCA may be at least comparable with the influence of changing the type of natural coarse aggregate. It is possible to prepare durable structural concretes with RCA. Concretes incorporating up to 25% RCA behave similarly to those prepared with 100% NCA, and taking proper precautions, it should be possible to obtain concretes with adequate durability by employing higher contents of RCA.

Conclusions

The influence of the type and content of RCA on the transport properties of recycled concrete was studied. As a reference, concretes made with different types of NCA were tested. The depth of water penetration under pressure, chloride diffusion coefficient, and capillary absorption were evaluated. The primary conclusions are presented in the following.

1. The durability of recycled concrete can be as good as that of concretes prepared with natural aggregates and similar compressive strength. Concretes incorporating up to 25% RCA behave similarly to those prepared with 100% NCA, and it is possible to obtain concretes with adequate durability by employing higher RCA contents (up to 75%).

2. The durable behavior of recycled concretes will be different according to the transport mechanisms to which they are exposed. Concrete porosity is reflected in the capillary absorption test by an increase of its parameters, either attributable to an increase in the content of RCA or to the use of highly porous natural aggregates. Regarding chloride diffusion, recycled concretes made with quartzite aggregates or river gravel showed better performance than the corresponding conventional concretes. The improvements in chloride binding capacity of recycled concretes are associated with the presence of mortar in the coarse aggregate particles.
3. Measurements of sorptivity, depth of water penetration under pressure, and chloride diffusion coefficients verify that the durability properties improve as the concrete compressive strength increases, showing the same tendency for both NCA and RCA concretes. In some cases, the durability properties tend to decrease in concretes with high contents of RCA, and when some porous natural aggregates are used.
4. In concretes of similar strength, the modifications in the transport properties caused by the use of RCA are comparable with the effect of changing the type of natural coarse aggregate in conventional concretes. The same range of variation in concretes containing up to 25% RCA was found, but when 75% RCA is used, the range of variation is slightly higher.

The conclusions apply to the NCA and RCA in the study. Extrapolation to other conditions and materials must be carefully analyzed.

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