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Performance of recycled concretes exposed to sulphate soil for 10 years

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HIGHLIGHTS

- Recycled coarse aggregates obtained from two different crushed waste concrete.
- Recycled concretes with variable content of recycled coarse aggregate.
- Recycled concretes with and without specific features against sulphate attack.
- Concretes exposed to sodium sulphate soil for more than 10 years.
- No major influence of the RCA content on the durability of concrete was determined.

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ABSTRACT

Recycled aggregate concretes, particularly those made with crushed concrete in replacement of the natural coarse aggregate, have been increasingly used in the last decades. Although compressive strength is not affected by the replacement of conventional coarse aggregates by recycled coarse aggregates (RCA), there is still some disagreement regarding their durable performance, particularly when they are exposed to severe conditions.

This study evaluates the performance of recycled concretes made with different RCA contents (25%, 50%, 75% and 100%) exposed to sulphate soil for more than 10 years. Concretes designed with and without provisions for durability to sulphate attack were exposed. The specimens were half buried in sulphate soil and their condition was periodically assessed by visual inspection, weight loss and dynamic modulus of elasticity. Additionally, the extent of the attack on mortar–coarse aggregates interfaces was studied by stereomicroscopy and optical microscopy. Results to date indicate similar performances for recycled aggregate concretes and natural aggregate concretes with the same compressive strength level, even for a 100% RCA content.

1. Introduction

Durability of concrete is related to its transport properties when exposed to external detrimental agents, which are closely linked to the water/cement ratio and hydration degree [1]. Wetting and drying cycles and wick action are some of the most unfavourable conditions to which concrete structures can be exposed. These processes are even more relevant when sulphates are present in the environment, and two different mechanisms of sulphate attack can occur: physical and chemical [2]. With respect to the physical mechanism, the external sulphate attack has three requirements to occur: concrete is highly permeable, the environment is rich in sulphates and water is present [3]. Moreover, other exposure conditions such as temperature, associated cation and sulphate concentration may also affect the mechanisms of deterioration [2,4,5].

In this sense, several studies of conventional concretes exposed to external sulphate attack have been carried out, and the cement type is always a key parameter that defines concrete performance. In a review concerning extended research on sulphate attack on mortars and concretes made with ordinary and blended cements, exposed to service conditions, Baghabra Al-Amoudi [6] concludes that blended cements, particularly those containing silica fume and blast-furnace slag, are highly resistant to sodium sulphate attack due to the reduction of the calcium hydroxyde (CH) from cement hydration, and the densification of the microstructure of the hardened cement paste. Low water/cement (w/c) ratios moderately alleviate sodium sulphate attack by mitigating the diffusion

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of sulphate ions through the cementitious matrix. Likewise, Irassar et al. [7] evaluated the deterioration of concrete specimens containing high volume of fly ash (40% of total cementitious material), natural pozzolan (40%) and ground-granulated blast-furnace slag (80%) exposed to sulphate soil, compared with those made with 100% ordinary portland cement and sulphate resisting portland cement. They conclude that, when the specimens are buried in sulphate soil, sulphate resistance of concretes containing high volume of mineral admixtures is similar to that of concrete made with sulphate resisting portland cement. This behaviour is attributed to the improvement of the characteristics of the paste-aggregate interface and the removal of CH, which lowers the formation of gypsum and ettringite. On the other hand, concretes with w/c: 0.52 presented extensive deterioration when they were semi-buried [8], due to the physical damage caused by crystallization of water-soluble sulphate salts. The authors conclude that the use of high contents of those supplementary cementitious materials improves the resistance to sulphate chemical attack, but reduces the resistance to physical attack.

The use of crushed waste concrete as coarse aggregate in the ready-mix concrete industry is an environment-friendly practice that has gained importance during the last decades. It allows reducing environment pollution and the extraction of non-renewable raw materials, and minimising costs associated with the transport of aggregates. Worldwide, the promotion of the use of construction and demolition waste has led to a significant number of recommendations on the use of these residues in concrete [9–13]. Generally, these recommendations establish maximum contents of between 20% and 35% of recycled coarse aggregate (RCA) obtained from crushing concrete for the production of new structural concrete.

Regarding mechanical performance, several studies indicate that the compressive strength levels achieved in recycled concretes are similar to those of concretes made with natural aggregates [14–20]. However, durable performance of recycled concretes is still a topic of concern due to the variability of results published and the different conclusions derived from them [21–23], particularly when recycled concretes are exposed under severe service conditions.

Recycled concrete is more porous than the strength-equivalent concrete totally made with natural aggregates, due to mortar attached to the RCA particles [24,25]. Although appropriate durable performance of recycled concrete exposed to different environments and transport mechanisms has been verified [26,27], little information on the exposure of recycled concrete to external sulphate attack can be found in the literature. Lee et al. [28] indicate that the absorption characteristics and replacement levels of recycled fine aggregates have a decisive influence on the sulphate resistance of mortar when exposed to sodium and magnesium sulphate solutions for 15 months. In other paper, Corral-Higuera et al. [29] evaluate the weight loss of concrete specimens exposed to sodium sulphate aqueous solution, and they conclude that the use of different supplementary cementitious materials contribute to increase the resistance to sulphate attack of concrete made with 100% RCA. Both studies used high-concentration solutions, and the performance of concrete or mortar may then differ from that under natural exposure, where concrete is not permanently saturated and wetting and drying cycles or wick action are possible.

For this reason, the main objective of this paper is to provide some information about the durable performance of recycled concretes exposed to sulphate attack under simulated service conditions. Concretes with and without provisions for durability to sulphate attack and made with variable contents of RCA (0%, 25%, 50%, 75% and 100%) were exposed to soil with a high content of sodium sulphate for more than 10 years. During this period, specimens were periodically evaluated by means of visual inspection, weight loss and resonant frequency. After 10 years of exposure, samples were taken for microscope observations.

2. Experimental

2.1. Materials and mixtures

In concrete production, ordinary portland cement (OPC) (equivalent to CEM I 42.5 N according to EN 197-1) and blended portland cement (BPC) (equivalent to CEM II/B-M (L-S) 42.5 N according to EN 197-1), containing 18% limestone filler and 12% granulated blast furnace slag, were used. Natural siliceous sand was used as fine aggregate and crushed granitic stone was employed as natural coarse aggregate (NCA). Two recycled coarse aggregates (RCAs) differing in their sources were also employed: RCA$_1$, which was obtained by crushing concrete with water/cement (w/c) 0.50, made with a moderately sulphate resisting cement (according to IRAM 50001:2010 [30], $4\% < C_3A < 8\%$); and RCA$_2$, which was obtained by crushing concretes with different and unknown characteristics but all them containing crushed granitic stone as coarse aggregate. The physical properties of fine and coarse aggregates are presented in Table 1. As expected, RCAs present higher water absorption and "Los Angeles" abrasion loss, and lower specific gravity than NCA. These differences are related to the old mortar attached to the RCA particles [24,31,32].

In order to obtain structural concretes with and without durable features, two series of concretes including different w/c ratios were made. In both series, NCA was replaced by RCAs by volume.

- Series 1 corresponds to concretes without durable features (w/c = 0.50): a conventional concrete (S1R0) containing natural aggregate, and two recycled concretes containing 25% and 75% RCA$_1$ (S1R25 and S1R75) were made, all of them with the same mixture proportions. The binder was ordinary portland cement (OPC), classified as moderately sulphate resisting cement.
- Series 2 corresponds to concretes with durable features (w/c = 0.35): a conventional concrete with 100% natural aggregate (S2R0) and three recycled concretes containing 50%, 75% and 100% RCA$_2$ (S2R50, S2R75, and S2R100) were made. In this series, blended portland cement (BPC), classified as moderately sulphate resisting cement, and an air-entraining admixture were used in all mixes.

Mixture proportions, fresh state properties (slump, unit weight and air content) and 28-day compressive strength (f'_c) for both concrete series are presented in Table 2. The coarse aggregates (natural and recycled) were used in the saturated state to counteract the higher absorption of RCAs with respect to NCA.

Cylindrical specimens (150 × 300 mm) for compressive strength and prismatic specimens (75 × 100 × 430 mm) for sulphate soil exposure were cast with each concrete. All specimens were placed in a fog room (T: 23 ± 2 °C; RH > 95%) until the age of 28 days. It should be mentioned that the concrete series were prepared at different stages, and the exposure periods are then different for each series.

Table 1
Properties of aggregates.

Properties	Fine aggregate	Coarse aggregates		
		NCA	RCA$_1$	RCA$_2$
Fineness modulus	2.47	7.30	6.69	6.99
Maximum size (mm)	–	25.4	19.0	25.4
Specific gravity (SG$_{ssd}$) (g/cm^3)	2.60	2.69	2.46	2.44
Absorption (%)	0.5	0.4	5.0	4.7
"Los Angeles" abrasion loss (%)	–	25.7	38.2	41.4

Table 2
Mixture proportions (kg/m^3).

Materials		Series 1			Series 2			
		S1R0	S1R25	S1R75	S2R0	S2R50	S2R75	S2R100
Water		155	155	155	145	145	145	145
Cement	OPC	310	310	310	–	–	–	–
	BPC	–	–	–	420	420	420	420
Fine aggregate		850	850	850	780	780	780	780
NCA		1040	780	260	990	490	245	–
RCA$_1$		–	240	715	–	–	–	–
RCA$_2$		–	–	–	–	450	670	900
Air-entraining admixture		–	–	–	0.126	0.126	0.126	0.126
Slump (mm)		85	100	80	120	110	100	100
Air content (%)		1.8	2.0	2.2	5.0	4.7	5.1	4.2
f'_c (MPa) 28-day		27.0	28.0	27.1	33.3	32.5	33.3	36.5

Fig. 1. Specimens at the experimental field.

2.2. Test procedure

After curing and before exposure in sulphate soil, each specimen was weighed and the dynamic modulus of elasticity was determined by means of the resonance frequency method. Next, specimens were placed in sulphate soil.

The soil of the experimental field consisted of saturated silty sand containing 1% of sodium sulphate, which represents a moderate aggression environment according to the Argentine Regulation (CIRSOC 201-2005) [33]. The climate at the location of the experimental field (La Plata, Argentina) is characterised by a rainfall of 1000 mm/year, average maximum temperature of 30 °C, average minimum temperature of 5 °C and average relative humidity of 78%. Fig. 1 show the specimens in the experimental field, which are protected by roof so that soil sulphate concentration is not affected by weather events.

Specimens were placed at the experimental field partially buried in relation to their longitudinal axis and rotated 90 degrees with respect to the casting direction (Fig. 2). Fig. 2a) indicates the faces during casting, where *t*, *b* and *l* refer to trowelled, bottom and lateral faces, respectively. Thus, trowelled (*t*) and bottom (*b*) casting faces of specimens were partially buried in soil (Fig. 2b). One of the lateral faces was exposed to the air (*l-top*), and the other completely immersed in the soil (*l-soil*). The same orientation was maintained during the whole exposure period.

The specimens were periodically evaluated, initially every 180 days and then every about 365 days. The evaluation consisted in visual inspection of each specimen and description of the different damage signs found (cracking, spalling, aggregates exposed, etc.), weighting and determination of resonant frequency according to ASTM C 215 [34].

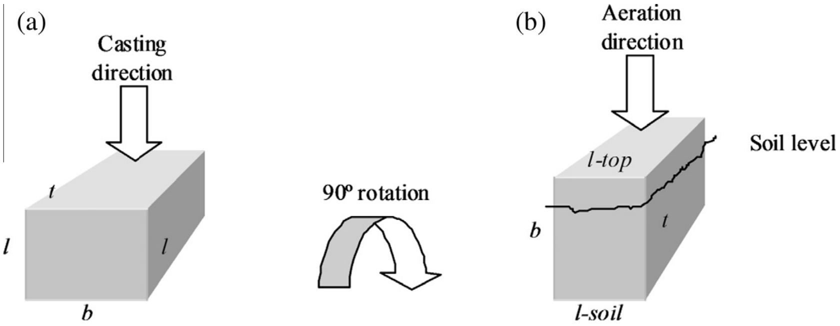

Fig. 2. (a) Casting faces of specimens, (b) location of faces at the exposure field.

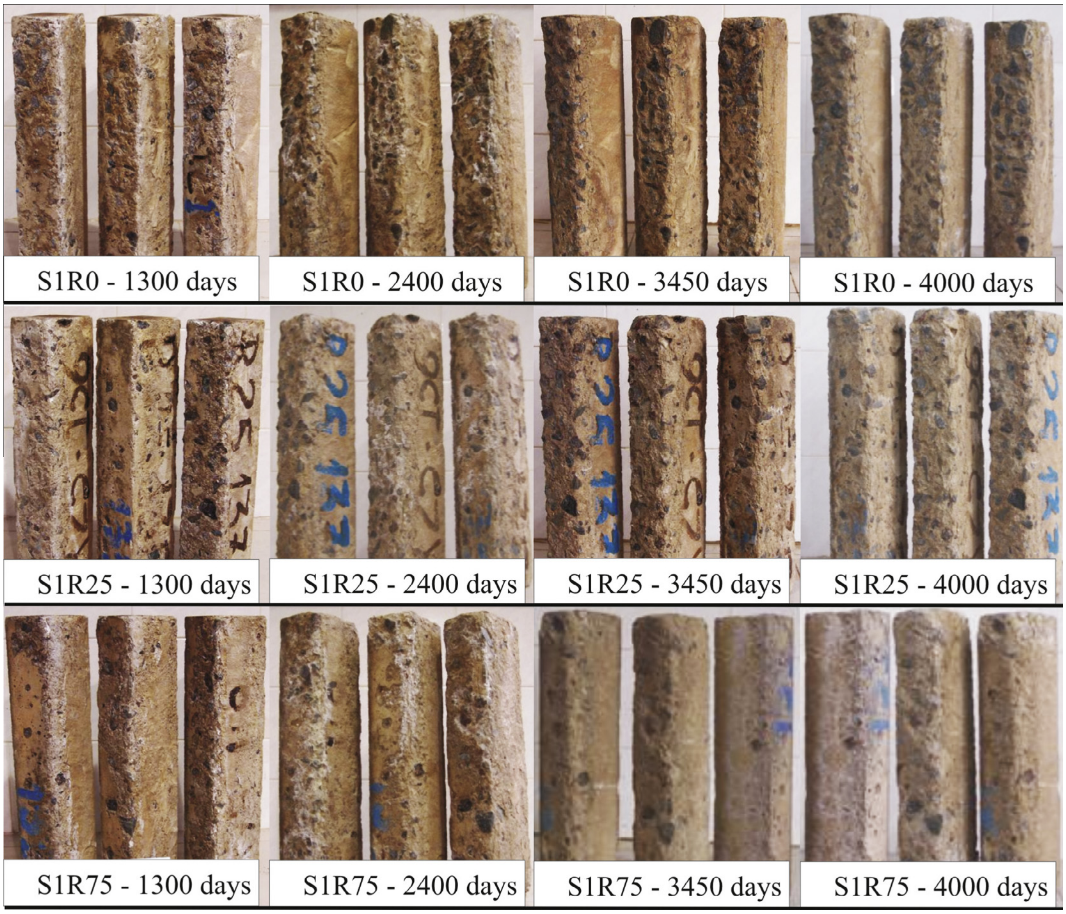

Fig. 3. Visual aspect of specimens of Series 1.

3. Results and analysis

With respect to the fresh state properties, it can be noted that for each concrete series, all mixtures presented similar slump and air content. In series 2, for the same doses of air-entraining admixture, it can be observed that concretes with different content of RCA presented similar air content (see Table 2). In this table, it can also be observed that within each concrete series recycled concretes have similar 28-day compressive strength value than the respective conventional concrete, including concrete made with 100% RCA.

3.1. Visual aspect

The variation of visual aspect due to superficial deterioration occurred along exposure time in conventional and recycled concretes from Series 1 can be observed in Fig. 3. No differences in the deterioration level derived from visual aspect for recycled and conventional concretes could be detected during all the evaluation period. This implies a relatively low impact of the increased porosity of recycled aggregates in comparison with natural aggregates and regarding physical attack by salt crystallization, whereas the use of moderately sulphate resisting cement in the original concrete resulted in a low sensibility to chemical attack by sulphates of recycled concrete.

It is known that deterioration due to the physical attack of sulphate occurs in the air exposed zone of specimens, because this zone is affected by the wick action that cause crystallization in pores and micro-cracking near concrete's surface [2]. At the age of 146 days, physical deterioration by sulphate attack began with spalling of cover mortar, mainly located at the *l-top* and semi-buried (*t*, *b*) faces (Fig. 2b). Some coarse aggregates were consequently exposed. For the exposure period of 1300 days, degradation in the *l-top* faces was generalised, with more than 90% of cover mortar detached, whereas degradation in the trowelled face (face *t*) occurred only in the air exposed zone. Longitudinal cracking near the edges and corners of these faces was observed at the age of 2765 days (Fig. 4). This cracking progressed and caused detachment with increasing exposure time. Edges and corners are particularly susceptible to this attack mechanism due to the multidimensional penetration of sulphate ions through both adjacent faces and because there is not lateral confinement to counteract the stresses induced by sulphate attack.

Fig. 4. Longitudinal cracking near the edges of adjacent faces.

With increasing spalling, coarse aggregates were directly exposed to sulphate attack and began detaching when mortar covering them was deteriorated. In the case of RCAs, detaching of natural aggregate particles requires that mortar contained in recycled aggregate particles is also deteriorated. This difference led to higher degradation of conventional concrete at early ages, as it could be seen with the evaluations of the dynamic modulus (see later).

A detail of specimens' condition corresponding to the Series 1 after 3450 days of exposure is presented in Fig. 5. Similar deterioration degrees of the specimens for all concretes are observed.

The external aspect of the specimens from Series 2 registered at different ages is presented in Fig. 6. From the comparison between Figs. 3 and 6 it can be observed that the aspect of specimens of the Series 2 is very different from that of Series 1. Differently from Series 1, in Series 2 there was no visual evidence of concretes degradation, including concrete made with 100% RCA. Several factors contribute for the better performance of the specimens of Series 2, such as a lower water/cement ratio, entrained air, and the use of BPC, which all contribute to reduce permeability and calcium hydroxide content. Then, it can be derived that the effect of these parameters was more significant than that of the content of RCA on the durable performance of concrete exposure to external sodium sulphate attack.

3.2. Weight variation

The weight variations for concrete specimens of Series 1 are presented in Fig. 7, where each point is the average value of three samples. It can be observed that recycled concretes made with up

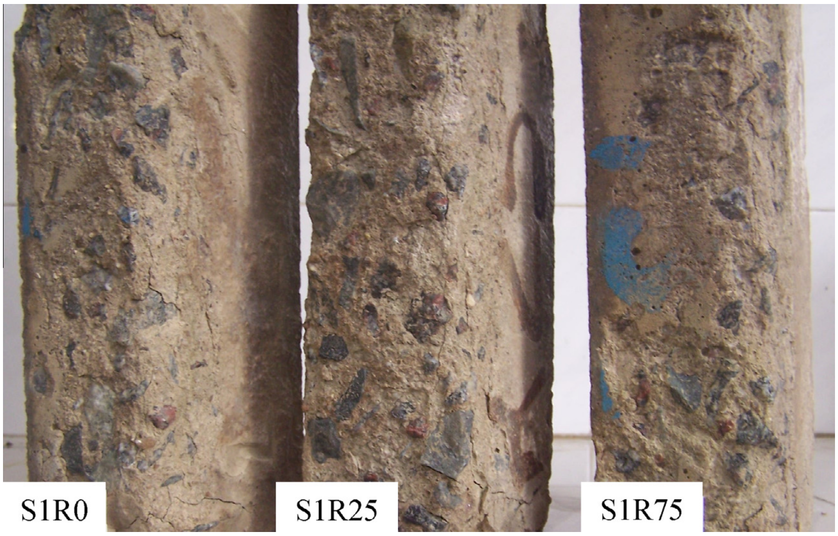

Fig. 5. Detail of specimens of Series 1 after 3450 days of exposure.

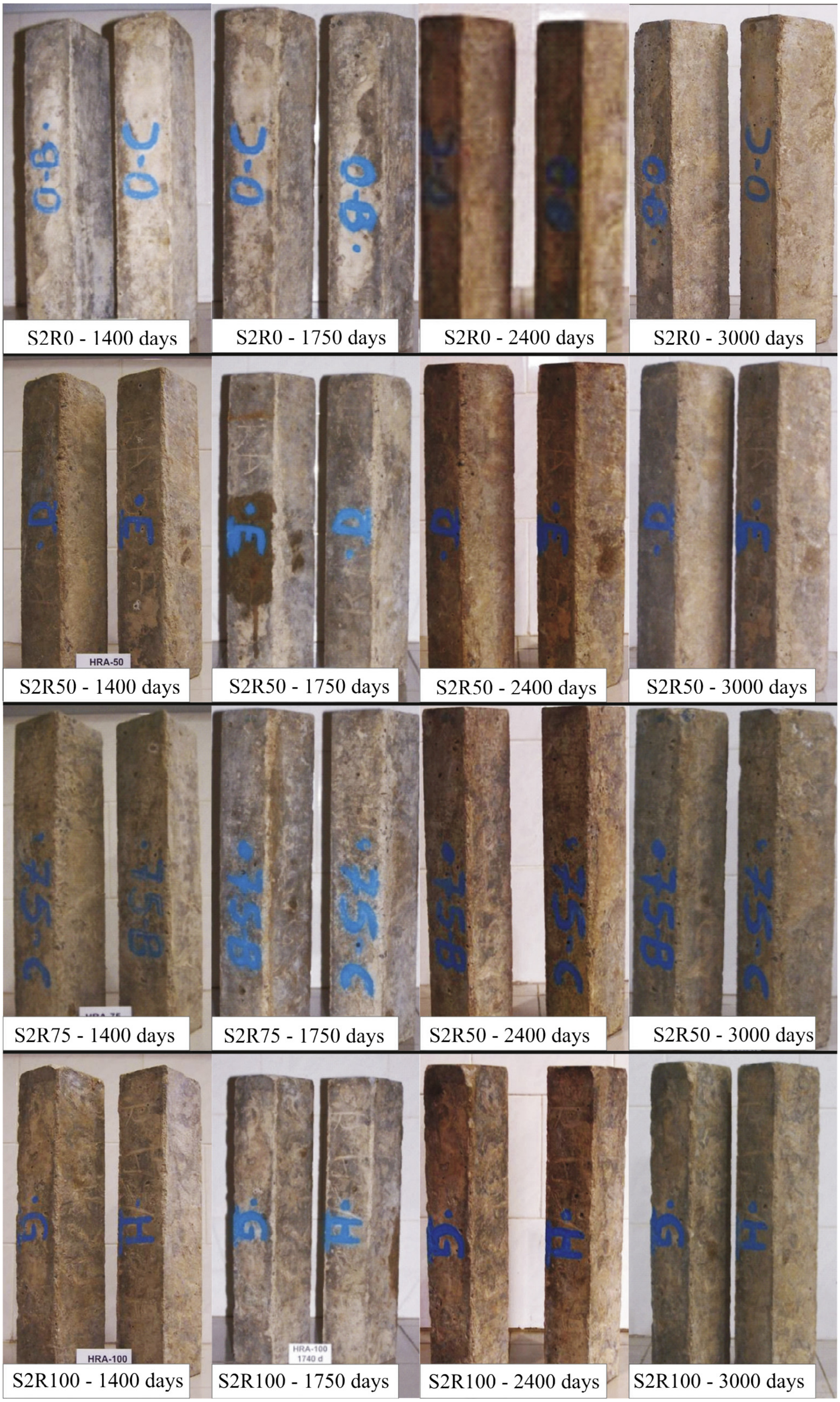

Fig. 6. Visual aspect of specimens of Series 2.

to 75% RCA show similar weight variations to those of conventional concrete. Both types of concretes showed reducing weight with exposure time due to physical degradation induced by crystallization of sulphate, as previously mentioned.

Fig. 8 shows the weight variations for concrete specimens in Series 2. Similar performance for recycled and conventional concretes is noted, including concrete with 100% RCA content. Contrary to the observations for Series 1, no weight reduction

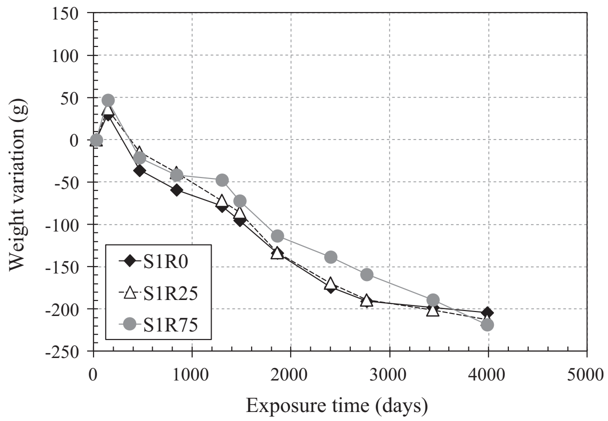

Fig. 7. Weight variation for concretes of Series 1.

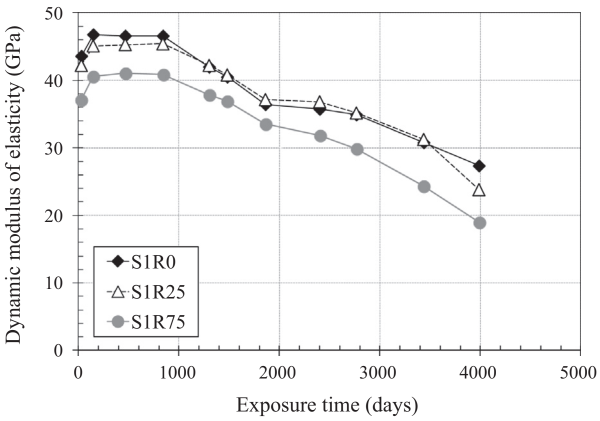

Fig. 9. Dynamic modulus of elasticity for Series 1.

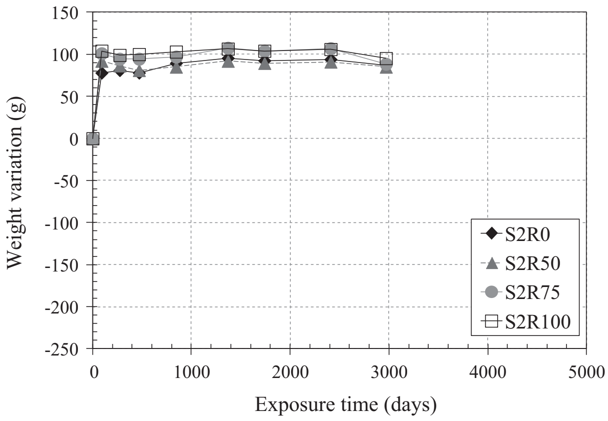

Fig. 8. Weight variation for concretes of Series 2.

is observed, a fact that confirms the results from visual inspection.

For both concrete Series, a slightly increment of weight is observed at the beginning of the exposure time. This fact can be attributed to the fact that specimens were cured in a fog room and they were further saturated in the experimental field.

3.3. Dynamic modulus of elasticity

The variation of the dynamic modulus of elasticity with time for Series 1 is presented in Fig. 9, where data correspond to the average of three measurements for each concrete type.

At the earlier ages, the value of the dynamic modulus of elasticity is in accordance with the density of each type of concrete because of the different specific gravity of RCA with respect to NCA. Until approximately 900 days of exposure time, values for the dynamic modulus of elasticity remain constant for all concretes. After this exposure time, the values for dynamic modulus gradually decreased in all concretes, as consequence of the degradation of the specimens. The decrease in the dynamic modulus is lower for concrete with higher content of RCA, reaching at the age of 1860 days 84, 88, and 90% of the initial modulus for S1R0, S1R25 and S1R75, respectively. This reduction is caused by the physical attack of sulphates, which precipitate in concrete pores and generate tensile stresses. This is confirmed by the extended cracking of specimens and loss in weight.

After 2400 days, a modification in the performance of concretes can be observed, where the dynamic modulus of S1R75 concrete decrease faster than for conventional concrete, as detachment of recycled aggregate particles and new mortar increases after this exposure period. This behaviour is consistent with the loss in weight observed in Fig. 7. At the last assessment period (4000 days), dynamic modulus of elasticity reaches relative values of 63, 56, and 51% for S1R0, S1R25 and S1R75, respectively, with respect to the values before exposure.

The variation of the dynamic modulus of elasticity with time for concrete of Series 2 is presented in Fig. 10, where each point corresponds to the average of two specimens. As well as for Series 1, the values of the dynamic modulus of elasticity decreases with increasing RCA content. Also, similar performance of recycled and conventional concretes is observed, with values nearly constant throughout 3000 exposure days. This fact was confirmed by the visual inspection of the specimens (Fig. 6), where no deterioration was observed. Again, this fact should be attributed to the low w/c ratio, the use of an air-entraining admixture and the use of blended portland cement, which lead to a very good performance of this concrete series.

3.4. Microscopic observations

Due to the high decrease in the dynamic modulus of elasticity and the observed deterioration of specimens, one specimen of each concrete of Series 1 was sawed at the last assessment period, to obtain samples that can be analysed by stereomicroscopy and optical microscopy. By stereomicroscope observation (Fig. 11), it was noted that mortar-NCA interfaces were cracked and filled. These cracks propagate through mortar and are filled by colourless materials to whitish material (A). In contrast, only in some of the superficial attacked areas filling was partially detected in the interfaces

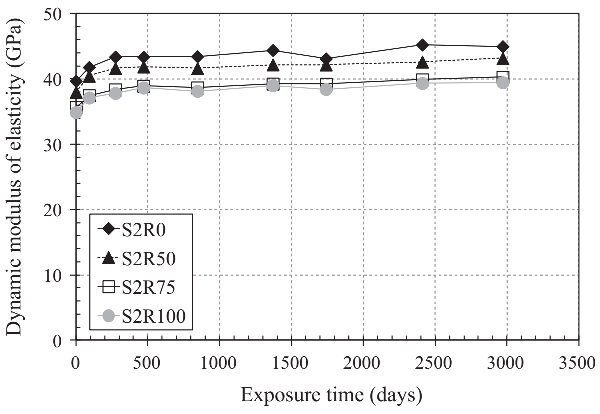

Fig. 10. Dynamic modulus of elasticity of Series 2.

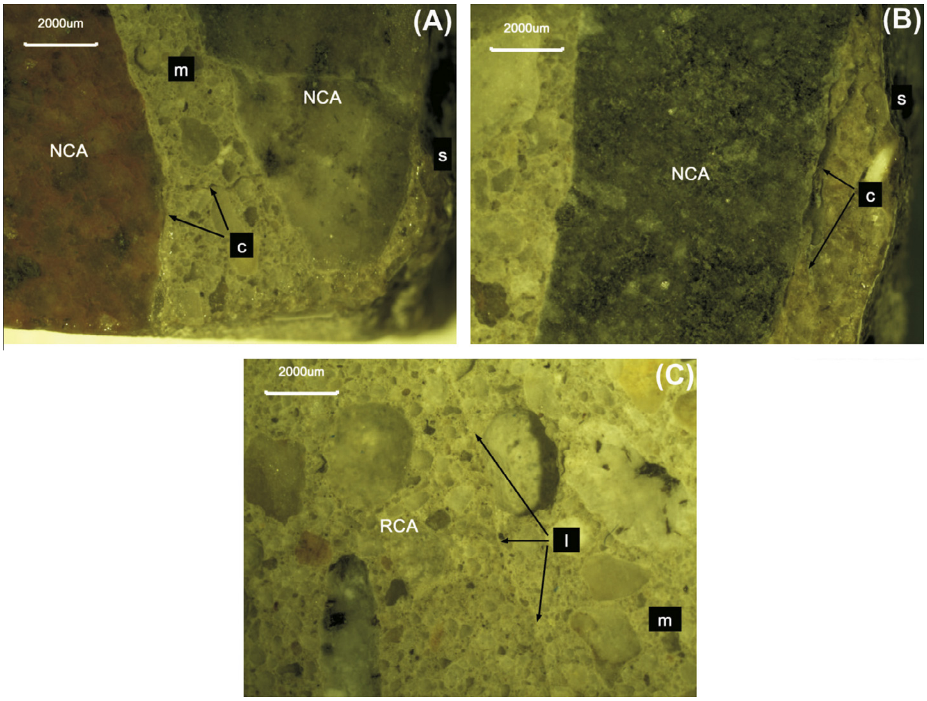

Fig. 11. Mortar-aggregate interfaces observed by stereomicroscope. NCA: natural coarse aggregate; RCA: recycled coarse aggregate; s: surface damaged by sulphate attack on a side face of the specimen; m: mortar; c: cracks; I: interfaces.

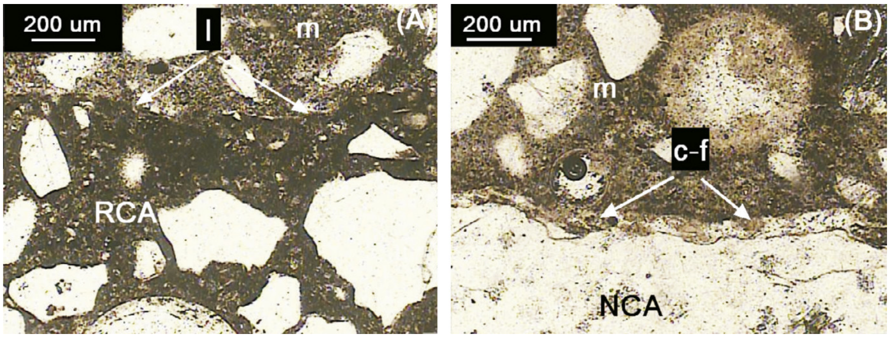

Fig. 12. Mortar-RCA and mortar-NCA interfaces observed by optical microscope RCA: recycled coarse aggregate; NCA: natural coarse aggregate; m: mortar; c-f: cracks partially filled; I: interfaces.

(B). In recycled concrete, new mortar-RCA interfaces are noted only by a slight change in colour between the two mortars. They are then continuous and strongly bonded (C).

Fig. 12 shows mortar-aggregate interfaces observed by optical microscope. Here, although similarly to observations from stereomicroscopy new mortar-RCA interfaces generally show strong bonding and continuity (A), some short microcracks were identified in specific sectors. In the region under sulphate attack, mortar-NCA interfaces are degraded, with cracks and filling products (B). These sectors are carbonated and cracks are clean or partially filled with fibrous materials of low birefringence, which corresponds to ettringite mixed with gypsum and calcite. The presence of ettringite was observed in pores at a maximum depth of 15 mm. Cracks up to 1 mm width were observed, which extend into the matrix and affect other interfaces.

4. Conclusions

This paper presents results obtained from the performance of concretes with and without specific features against sulphate attack, which were made with recycled coarse aggregate (RCA) up to 100% content, and ordinary and blended portland cement. Concretes were exposed to sulphate soil for more than 10 years and periodically assessed by visual observation, loss in weight, dynamic modulus of elasticity and microscopic observation.

Conventional and recycled concretes with up to 75% RCA content, designed without specific features against sulphate attack, presented a similar degradation level for at least 4000 days of exposure in sulphate soil. The visual inspection confirmed that the most vulnerable sectors were edges and corners of specimens, and that the highest degradation also occurred in the air exposed zone, where concrete was affected by the wick action. From the values of the dynamic modulus of elasticity, a similar decrease rate in the soundness, starting after 900 days of exposure, was observed for conventional and recycled concretes. The observed behaviour could be attributed to a similar resistance to salt crystallization, whereas the use of moderately sulphate resisting cement in the original concrete contributed to avoid an increase in the deterioration rate due to a reaction between sulphates and recycled aggregates.

In the case of concretes designed for durability in aggressive environments such as sulphate soil, conventional and recycled concrete with up to 100% RCA content, made with a low w/c ratio, blended portland cement and entrained-air, showed an excellent performance for at least 3000 days of exposure.

As a general conclusion, no significant influence of the RCA content on the durable performance of concrete exposed to sulphate soil was determined.

References

[1] S. Mindess, J.F. Young, in: N.M. Newmark, W.J. Hall (Eds.), Concrete, Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1981. 07632.

[2] A. Neville, The confused world of sulfate attack on concrete, Cem. Concr. Res. 34 (8) (2004) 1275–1296.

[3] M. Collepardi, A state-of-the-art review on delayed ettringite attack on concrete, Cem. Concr. Compos. 25 (4–5) (2003) 401–407.

[4] M. Santhanam, M.D. Cohen, J. Olek, Sulphate attack research – whither now?, Cem Concr. Res. 31 (6) (2001) 845–851.

[5] H.A.F. Dehwah, Effect of sulphate concentration and associated cation type on concrete deterioration and morphological changes in cement hydrates, Constr. Build. Mater. 21 (1) (2007) 29–39.

[6] O.S. Baghabra Al-Amoudi, Attack on plain and blended cements exposed to aggressive sulfate environments, Cem. Concr. Compos. 24 (3–4) (2002) 305–316.

[7] E.F. Irassar, O.R. Batic, A. Di Maio, J.M. Ponce, Sulfate resistance of concrete containing high volume of mineral admixtures, in: 7th CANMET/ACI International Conference on Durability of Concrete, Montreal, CA. American Concrete Institute, 2006, SP-ACI; 234, pp. 589–606.

[8] E.F. Irassar, A.A. Di Maio, O.R. Batic, Deterioro del hormigón por cristalización de sales, in: VI Congreso Internacional sobre Patología y Recuperación de Estructuras (CINPAR), Córdoba, Argentina, 2010. (Edited in CD) (in Spanish).

[9] T.C. Rilem, 121-DRG. Specifications for concrete with recycled aggregates, Mater. Struct. 27 (9) (1994) 557–559.

[10] P. Grübl, M. Rühl. German committee for reinforced concrete (dafstb) – code: concrete with recycled aggregates, in: Int. Symposium Sustainable Construction: Use of Recycled Concrete Aggregates. Thomas Telford Limited, Thomas Telford House, 1 Heron Quay, London E14 4JD, UK, 1998. Available in <www.b-i-m.de>.

[11] EHE. Instrucción de Hormigón Estructural. Anejo 15, Recomendaciones para la utilización de hormigones reciclados, 2008. Available in <www.fomento.es>.

[12] G.L. Balázs, T. Kausay, T.K. Simon, Technical guideline for recycled aggregate concrete in Hungary, Concr. Struct. 9 (2008) 45–55.

[13] K. Sagoe-Crentsil, T. Brown, Guide for specification of recycled concrete aggregates (RCA) for Concrete Production - Final Report. CSIRO, Building, Construction and Engineering, 1998. PO Box 56, Highett Road, Victoria. 3190.

[14] T.C. Hansen, H. Narud, Strength of recycled concrete made from crushed concrete coarse aggregate, Concr. Int. 5 (1) (1983) 79–83.

[15] Rasheeduzzafar, A. Khan, Recycled concrete – a source for new aggregate, Cem. Concr. Aggreg. 6 (1) (1984) 17–27.

[16] M.C. Limbachiya, T. Leelawat, R.K. Dhir, Use of recycled concrete aggregate in high-strength concrete, Mater. Struct. 33 (9) (2000) 574–580.

[17] A. Ajdukiewicz, A. Kliszczewicz, Influence of recycled aggregates on mechanical properties of HS/HPC, Cem. Concr. Compos. 24 (2) (2002) 269–279.

[18] A.A. Di Maio, C.J. Zega, L.P. Traversa, Estimation of Compressive Strength of Recycled Concrete with the Ultrasonic Method, J. ASTM Int. 2 (5) (2005). Available in www.astm.org.

[19] A.K. Padmini, K. Ramamurthy, M.S. Mathews, Influence of parent concrete on the properties of recycled aggregate concrete, Constr. Build. Mater. 23 (2) (2009) 829–836.

[20] S.W. Tabsh, A.S. Abdelfatah, Influence of recycled concrete aggregates on strength properties of concrete, Constr. Build. Mater. 23 (2) (2009) 1163–1167.

[21] A. Gonçalves, A. Esteves, M. Vieira, Influence of recycled concrete aggregates on concrete durability, in: E. Vázquez, Ch.F. Hendriks, G.M.T. Janssen (Ed.), International RILEM Conference on The use of recycled materials in building and structures, Barcelona, Spain, RILEM, 2004, pp. 554–562.

[22] N. Otsuki, S. Miyazato, W. Yodsudjai, Influence of recycled aggregate on interfacial transition zone, strength, chloride penetration and carbonation of concrete, J. Mater. Civil Eng. 15 (5) (2003) 443–451.

[23] S.M. Levy, P. Helene, Durability of recycled aggregates concrete: a safe way to sustainable development, Cem. Concr. Res. 34 (11) (2004) 1975–1980.

[24] J.M. Gómez, L. Agulló, E. Vázquez, Cualidades físicas y mecánicas de los agregados reciclados de concreto, Construcción y Tecnología 13 (157) (2001) 10–20.

[25] C.J. Zega, A.A. Di Maio. Influencia de las características de los agregados reciclados en la elaboración de hormigones, in: Memorias 15 Reunión Técnica de la AATH, Santa Fe, Argentina, 2003. (Edited in CD) (in Spanish).

[26] C.J. Zega, V.L. Taus, A.A. Di Maio, Effect of entrained air on recycled concrete properties, J. ASTM Int. 3 (10) (2006). Available in www.astm.org.

[27] Y.A. Villagrán-Zaccardi, C.J. Zega, A.A. Di Maio, Chloride penetration and binding in recycled concrete, J. Mater. Civil Eng. 20 (6) (2008) 449–455.

[28] S. Lee, R. Swamy, S. Kim, Y. Park, Durability of mortars made with recycled fine aggregates exposed to sulfate solutions, J. Mater. Civil Eng. 20 (1) (2008) 63–70. Special issue: Durability and service life of concrete structures: recent advances.

[29] R. Corral-Higuera, S.P. Arredondo-Rea, M.A. Neri-Flores, J.M. Gómez-Soberón, F. Almeraya-Calderón, J.H. Castorena-González, J.L. Almaral-Sánchez, Sulfate attack and reinforcement corrosion in concrete with recycled concrete aggregates and supplementary cementing materials, Int. J. Electrochem. Sci. 6 (3) (2011) 613–621.

[30] IRAM 50001. Cement. Cements with special properties (in Spanish). Instituto Argentino de Normalización y Certificación, Buenos Aires, Argentina, 2010.

[31] C.J. Zega, Recycled concretes: characterization of recycled coarse aggregates (MSc Thesis), 2008, 135p. (in Spanish). Available in www.fio.unicen.edu.ar.

[32] M. Sánchez de Juan, P. Alaejos Gutiérrez, Study on the influence of attached mortar content on the properties of recycled concrete aggregate, Constr. Build. Mater. 23 (2) (2009) 872–877.

[33] CIRSOC 201. Reglamento Argentino de Estructuras de Hormigón. Instituto Nacional de Tecnología Industrial, Buenos Aires, Argentina, 2005.

[34] ASTM C 215–02, Standard test method for fundamental transverse, longitudinal and torsional frequencies of concrete specimens. Annual Book of ASTM Standards, vol. 04.02 Concrete and Aggregates, 2008.