Influence of curing conditions on recycled aggregate concrete

C. Thomas[a, *]

carlos.thomas@unican.es

J. Setién[a]

J.A. Polanco[a]

A.I. Cimentada[a]

C. Medina[b]

[a]LADICIM (Laboratory of Materials Science and Engineering), University of Cantabria. E.T.S. de Ingenieros de Caminos, Canales y Puertos, Av/Los Castros 44, 39005 Santander, Spain

[b]University of Extremadura, UEX-CSIC Partnering Unit, School of Civil Engineering, Avda. de la Universidad, s/n, Cáceres, Spain

*Corresponding author.

Abstract

This paper presents the results of a study of permeability and its influence on the durability of recycled concrete exposed to an aggressive environment. Recycled concretes with 20%, 50% and 100% in weight of recycled aggregate and 24 effective w/c ratios have been exposed directly to a marine environment. Control specimens cured in a humidity chamber have been also tested in order to compare the influence of the curing environment. The durability of recycled aggregate concretes exposed to aggressive conditions decreases in terms of permeability, as the results show. However, the influence of the environment on the recycled concrete also depends on the quality of the cement paste. The differences between the control and the exposed concrete are lower for low water/cement (w/c) ratios. The lower capillarity obtained in the new cement paste of the recycled concretes with low w/c ratios isolates the porosity of the recycled aggregate, increasing the durability but with a rise in the cement content.

Keywords: Waste; Recycled aggregate concrete; Marine environment; Recycling; Mechanical testing; Durability

1 Introduction

The search for ways of using recycled aggregate (RA) from construction and demolition wastes (C&DW) in the production of recycled aggregate concrete (RC) has been going on for many years. Most researchers agree about the reduction in the physical and mechanical properties and the durability [1]. However, there are no comparable results on the durability of RC exposed to marine environments due to the heterogeneity of the RA, the w/c ratios and the types of cement used in different countries. Different studies [1-4] show that permeability, carbonation and risk of reinforcement corrosion increase when RC is used. However, no information is found in the literature about how the w/c ratio and capillary network affect the durability of RC exposed to a marine environment. A recent study shows that the durability of recycled concrete depends on the quality of the RA and that the most suitable RA comes from precast-structural concretes [2]. Also, several studies have analysed the behaviour of RC under cyclic stress (fatigue) [5-8], showing that the negative effect of the incorporation of recycled aggregate is significantly higher in the case of dynamic rather than static conditions. Other authors have found solutions, using other recycled materials, to improve the properties of the cement paste. Using this method, the effect of the RA [9] can be minimised, <u>not only in no-cement but also in polymeric matrixes</u> [10]. The use of RA containing contaminants such as sulphur and properties of recycled aggregate mortar (RAM) and RC has also been studied [11], finding a reduction in the quality of the concrete proportional to the quality of the recycled aggregate.

This paper presents the results of a study of permeability and its influence on the durability of recycled concrete exposed to an aggressive environment. On the one hand, the effect of RA on concrete properties has been analysed by studying the same w/c ratios and, on the other hand, the influence of the w/c ratio and its capillary network has been measured for equivalent degrees of RA. With this aim, RC with 20%, 50% and 100% wt of RA and 24 effective w/c ratios have been exposed directly to a marine environment.

2 Experimental program

This research is a continuation of a previous study and uses 6 control concretes (CC) made up of natural limestone aggregate (NA) and 18 substitutions of 20%, 50%, 100% of coarse NA with recycled aggregates (RA). The RA comes from demolished structural concrete (over 10 years old) with more than 25 MPa. The properties of the concrete at the age of 28 days cured in a standard environment and in XS1 environment [12] have been studied.

2.1 Materials

Portland cement CEM I 52,5N/SR of 3.11 g/cm^3 and Blaine fineness of 361 m^2/kg was used. Table 1 shows the chemical composition by XRF of the cement. Table 2 shows the NA and RA properties. Fig. 1 shows the aggregate grading including the natural sand (NS).

Table 1 Chemical composition of the cement.

Component:	CaO	SiO_2	SO_3	Al_2O_3	Fe_2O_3	MgO	K_2O	TiO_2	C
% in wt:	69.60	18.60	3.22	3.10	2.66	1.17	0.54	0.17	0.47

Table 2 Properties of the aggregate.

Aggregate	Dr [g/cm^3]	Dssds [g/cm^3]	A [% wt]	P [% v.]	Dc [g/cm^3]	LA [%]
NA (6/12)	2.510	2.550	1.80	4.70	1.530	31.0
NA (12/20)	2.540	2.590	1.60	4.00	1.530	–
RA (6/20)	2.320	2.310	5.30	12.30	1.420	42.0

Where: Dr is the relative density of particle (g/cm^3); Dssds is the saturated with dry surface density (g/cm^3); A is the water absorption in weight (%wt); P is the open porosity in volume (% vol.); Dc is the bulk density (g/cm^3); LA is the Los Angeles index (%).

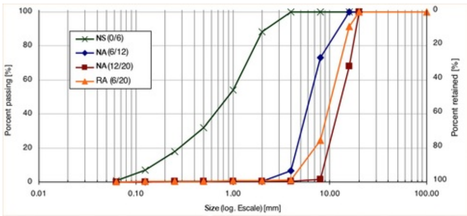

Fig. 1 Grading of the natural and recycled aggregates.

2.2 Mix proportions

The mixing specifications of four different environments were considered: a 0.65 w/c ratio concrete for a non-aggressive environment, Class X0 for an environment with no risk of corrosion or attack; a 0.55 w/c ratio concrete for an exposure class of corrosion induced by carbonation, XC; a 0.50 w/c for a marine air exposure, XS1-Corrosion induced by chlorides from sea water; and a 0.45 w/c for a marine environment (tidal and splash zone exposure), XS3-Corrosion induced by chlorides from sea water. Table 3 shows the mix proportions, the effective w/c ratios and the new properties. Three different mixing methods have been followed in three phases. In the first phase, dry coarse aggregate has been used. In this phase, RC-X0-DA and RC-XS1-DA, both the coarse NA and the coarse RA used were dry at the time of mixing. In a second phase, coarse saturated aggregates have been used. In order to avoid the effect of the higher absorption of the RA, both the NA and the RA have been presaturated with water before being incorporated into the mixture: RC-X0-SA and RC-XS1-SA. In a third stage, only the coarse RA is saturated. In this last phase, the coarse NA is incorporated dry and the coarse RA is incorporated saturated to the mixture: RC-XC-SR and RC-XS3-SR. The effective w/c ratio is obtained by the method proposed by Sanchez and Alaejos [13,14] taken at 70% of the absorption capacity during mixing using dry aggregates.

Table 3 Concrete mix proportions and fresh properties.

Designation	RC-X0-DA				RC-X0-SA				RC-XC-SR				RC-XS1-DA				RC-XS1-SA				RC-XS3-SR			
RA content	0%	20%	50%	100%	0%	20%	50%	100%	0%	20%	50%	100%	0%	20%	50%	100%	0%	20%	50%	100%	0%	20%	50%	100%
NS (kg):	840	880	850	870	950	960	980	1010	875	800	830	825	715	745	710	715	805	815	820	835	815	700	740	745
NA (12/20) (kg):	750	565	350	0	515	380	210	0	755	630	370	0	880	665	415	0	700	520	290	0	870	750	430	0
NA (6/12) (kg):	226	170	105	0	490	362	200	0	255	210	125	0	120	90	60	0	330	245	135	0	170	145	85	0
RA (12/20) (kg):	0	185	455	830	0	185	410	640	0	210	490	925	0	190	470	875	0	190	430	685	0	225	515	965
Cement (kg):	275	275	275	275	275	275	275	275	325	325	325	325	380	380	380	380	380	380	380	380	385	385	385	385
Water (kg):	180	180	180	180	180	180	180	180	180	180	180	180	190	190	190	190	190	190	190	190	173	173	173	173
Effective w/c ratio:	0.60	0.59	0.57	0.54	0.67	0.68	0.67	0.70	0.51	0.52	0.54	0.58	0.46	0.45	0.44	0.42	0.53	0.53	0.53	0.52	0.42	0.42	0.44	0.49
Slump (cm):	17	21	16	15	15	18	17	17	16	15	17	18	16	18	15	14	20	19	18	21	18	17	17	19

2.3 Specimens and curing conditions

More than 600 standard cylindrical specimens [15,16] were prepared and distributed in the two environments: first, in a humidity chamber at 20 °C and 95% humidity and, second, under direct exposure to a marine environment: Type IIIa with a one-year average temperature of 13.9 ± 5 °C temperature and 74.3 ± 2% humidity.

2.4 Mechanical properties

A Compressive strength test [17,18] and a Tensile splitting test [19] were performed on 3 specimens of each mix with 28 days curing. The modulus of elasticity was performed following the standard [20].

2.5 Physical properties

Standard [21] was followed in order to obtain the physical properties. Also, the water absorption coefficient and the open porosity of the concrete were determined.

2.6 Permeability

The maximum water penetration was determined following standard [22]. The oxygen permeability coefficient was determined according to [23].

2.7 Accelerated chloride penetration

In order to evaluate the chloride penetration, an accelerated test in a salt fog spray cabinet was carried out. After 250 h of exposure, eight subspecimens were obtained from four specimens to evaluate the degree of the chloride ion penetration. Compositional analyses by Energy-dispersive X-ray spectroscopy (EDAX) were performed to determine the profile of chloride ion penetration. A detailed explanation of how the measurements were performed is provided in [11].

3 Results and discussions

The results and discussion are presented in this section. The results of the concretes cured in a marine environment are compared with the results of the concretes cured in a humidity chamber [1].

3.1 Mechanical properties

Fig. 2 shows the compressive strength of the recycled concrete after 28 days of curing. The results indicate that curing under the marine environment leads to significant changes with respect to the standard environment [1] both for the control and the recycled concretes. According to [1], a similar recycled concrete cured a humidity chamber reached 60 MPa for a 0.4 w/c ratio and 35 MPa for a 0.75 w/c ratio. Hence, the loss of compressive strength due to curing environment is 12 MPa (15%) and 5 MPa (12%), respectively. According to these results, concretes cured in a marine environment show a significant loss of compressive strength, which is higher for the control concrete and lower w/c ratios. For higher w/c ratios, the reduction is not significant. The higher reduction of the compressive strength of concretes with higher quantities of cement indicates that this is due to defective hydration conditions. The differences between the control and the recycled concretes are less significant and there is not a greater decrease for concrete with a high cement content when using recycled aggregate. Mefteh, H. [24] evaluated the mechanical properties of recycled concretes cured under different moisture conditions. It was found that the compressive strength decreases by 8% when the recycled aggregate substitution is higher than 40%wt In [5,6], a greater reduction in mechanical properties for the higher w/c ratios was found. In the present work, the results show that this reduction depends on the w/c ratio. For w/c ratios under 0.45, the reduction in the 100% substitution is around 10%. However, for w/c ratios over 0.65, the reduction due to the marine environment is situated around 6%.

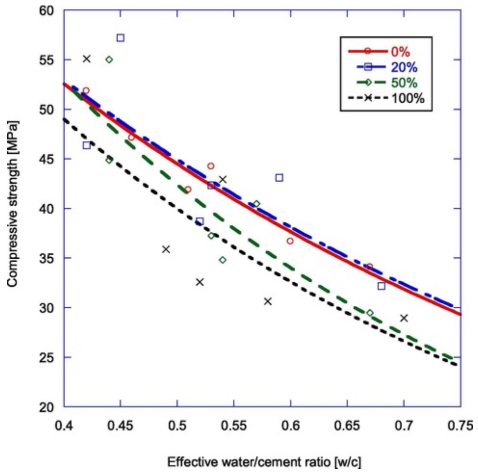

Fig. 2 Compressive strength of recycled concretes with 28 days cured into marine environment.

The replacement of natural aggregate by dry recycled coarse aggregate leads to a reduction in the water/cement ratio proportional to the degree of substitution. In Table 4, the effective volume of water (EW) and the effective volume of concrete (EV) of the mix are evaluated. The reduction in the volume of water leads to an increase in the amount of cement by cubic meter, increasing the cost of the concrete and negatively affecting the environmental benefits derived from the use of recycled aggregates. Hence, the Binder Intensity [25,26] has been calculated. This value has been obtained by measuring the reduction in volume and resistance to compression and the amount of cement per cubic meter required to increase the resistance by 1 MPa. The main consequence of the increase in the amount of cement per volume and the reduction in the w/c ratiois the increase in the compressive strength of the concrete with a higher degree of incorporation of dry RA, as can be seen in Table 4, for RC-X0-DA and RC-XS1-DA. According to the values obtained, the effect of curing in a marine environment reduces the compressive strength of the 100% recycled concrete to a value equivalent to a loss of 4.5%wt of the content of cement, being more significant for low w/c concretes.

Table 4 Mechanical properties of concretes and binder index.

Designation	RC-X0-DA				RC-X0-SA				RC-XC-SR				RC-XS1-DA				RC-XS1-SA				RC-XS3-SR			
RA content:	0%	20%	50%	100%	0%	20%	50%	100%	0%	20%	50%	100%	0%	20%	50%	100%	0%	20%	50%	100%	0%	20%	50%	100%
CS HC (MPa):	37.64	41.22	42.53	44.87	36.13	32.39	30.7	29.71	51.3	50.3	54.25	55.57	45.01	43.25	40.63	40.92	47.19	43.44	40.54	32.9	57.98	52.9	44.92	40.12
CS ME (MPa):	36.67	43.11	40.49	42.91	34.08	32.17	29.48	28.94	47.12	57.19	55.01	55.09	44.22	42.33	37.25	32.6	41.85	38.71	34.81	30.64	51.83	46.38	44.85	35.9
EW (m^3):	165.0	162.2	156.7	148.5	184.2	187	184.2	192.5	174.8	171.0	167.2	159.6	201.4	201.4	201.4	197.6	165.7	169.0	175.5	188.5	161.7	161.7	169.4	188.6
EV(m^3):	0.986	0.983	0.978	0.970	1.005	1.008	1.005	1.014	0.985	0.981	0.977	0.970	1.011	1.011	1.011	1.008	0.987	0.990	0.997	1.010	0.989	0.989	0.996	1.016
C/EV (kg/m^3):	278.9	279.7	281.3	283.7	273.6	272.8	273.6	271.3	385.9	387.4	388.9	391.9	375.7	375.7	375.7	377.1	329.4	328.3	326.1	321.9	389.4	389.4	386.4	379.1
BI HC (kg/m^3·MPa^{-1}):	7.4	6.8	6.6	6.3	7.6	8.4	8.9	9.1	7.5	7.7	7.2	7.1	8.3	8.7	9.2	9.2	7.0	7.6	8.0	9.8	6.7	7.4	8.6	9.4
BI-ME (kg/m^3·MPa^{-1})	7.6	6.5	6.9	6.6	8.0	8.5	9.3	9.4	8.2	6.8	7.1	7.1	8.5	8.9	10.1	11.6	7.9	8.5	9.4	10.5	7.5	8.4	8.6	10.6

CS HC is the compressive strength of the concrete cured into the humidity chamber;

CS ME: is the compressive strength of the concrete cured into the marine environment;

EW is the effective water volume;

EV is the effective volume of concrete;

C/EV is the cement/concrete volume index;

BI HC is the Binder Index of the concrete cured into the humidity chamber;

BI ME is the Binder Index of the concrete cured into the marine environment.

Fig. 3 shows the tensile splitting strength of the recycled concrete cured in marine environments. Fig. 3 show a loss in the tensile splitting strength due to the use of RA. Barbudo et al. [27] found a 12% decrease in the splitting tensile strength for a total replacement of NA by RA, explaining this by the fact that the bond between the cement paste and the recycled aggregates is weaker. Another study points out a reduction of between 5 and 20% depending on the w/c ratio of the concrete, higher for the w/c ratios over 0.7 [1]. However, when using high quality RA, the decrease in the tensile splitting strength for 20 and 50% of substitution is not significant [2]. The marine curing conditions, worse than the standard ones, attenuate the negative effect of the RA on the mechanical properties.

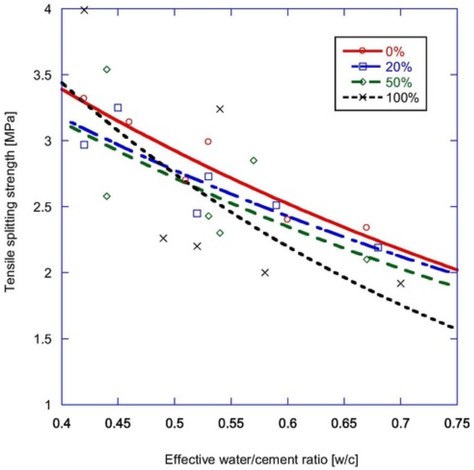

Fig. 3 Tensile splitting strength of recycled concretes with 28 days cured into marine environment.

3.2 Relative density

Fig. 4 shows the relative density of recycled concrete exposed to the marine environment. The density decreases linearly with the w/c ratio but shows a higher increment of the slope for the different degrees of substitution than in the case of the concretes cured a standard environment [1]. The density of the CC cured under a marine environment is approximately 1% lower than under a standard curing environment [1]. A similar tendency is observed for the recycled concrete with low w/c ratios. However, for high w/c ratios, the decrease in the density due to the marine environment is higher. On the one hand, the decrease in the density of the concrete exposed to the marine environment is due to the lower temperature and humidity of the curing conditions and subsequent less hydrated cement. On the other hand [28], the density is hardly affected by the density of the aggregate, even when the substitution is 100%.

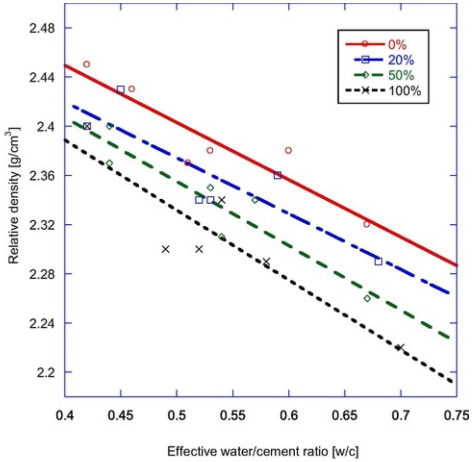

Fig. 4 Relative density of recycled concretes with 28 days cured into marine environment.

3.3 Absorption coefficient

Fig. 5 shows the values of the absorption coefficient of the concrete cured in a marine environment for different effective w/c ratios. The higher absorption observed for the higher w/c ratios when cured in the marine environment, similar to that observed for the standard environment [1], is the result of a more permeable cement paste. Also, the absorption coefficient increases with the degree of RA substitution. The absorption of the 100% RC with 0.65 w/c cured in a marine environment increases from 6.5% to 8.6%, a lower gap than that observed for the concrete cured in a standard environment due to the increase in the absorption of the CC [1]. Other authors [29] find that the water absorption coefficients of RC are 15% higher than CC, although the differences between concretes made with different recycled fine aggregates content were not reported. It follows that the environment does not have a marked influence on this property. The negative effect of recycled aggregate is significantly lower for low w/c ratios and similar for both environments. The cement paste with a low w/c ratio is less absorbent and the absorption due to the RA is in part isolated.

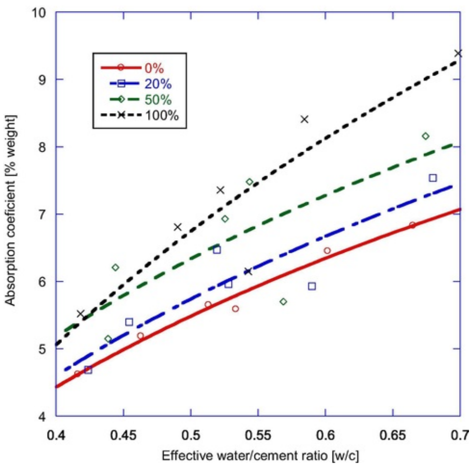

Fig. 5 Absorption coefficient of recycled concretes with 28 days cured into marine environment.

3.4 Porosity

Fig. 6 shows the open porosity of the concretes cured in a marine environment for different effective w/c ratios. The logarithmic curves converge for lower w/c ratios. Thus, the incorporation of RA reduces the durability of concretes with less cement content per cubic meter. Regarding the differences between the standard and marine environment [1], it is shown that the open porosity increases with the w/c ratio. And this increase is higher when greater quantities of RA are incorporated. Richardson [30] found that recycled concretes are slightly more durable than those made with natural aggregate in the freeze/thaw test, probably because of this greater porosity.

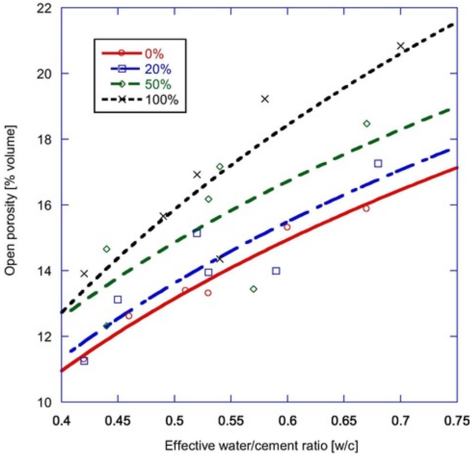

Fig. 6 Open porosity of recycled concretes with 28 days cured into marine environment.

3.5 Water penetration

Fig. 7 shows the water permeability of the concrete cured in a marine environment. The water depth observed is higher for high w/c ratios and increases with the incorporation of RA. For 0.45 w/c, the water penetration is between 34 and 38 mm (0% and 100% substitution), 20% and 10% higher than the result reported for a standard environment [1]. The curves tend to converge to water penetration values of 30 mm, corresponding to a compressive strength of 60 MPa. For the maximum penetration of 50 mm, the upper limit fixed by standard EHE-08 for IIIac environments, the w/c ratio of the CC should be 0.7 (compressive strength of 35 MPa) while for 100% RC the w/c ratio should be 0.55 (compressive strength 40 MPa).

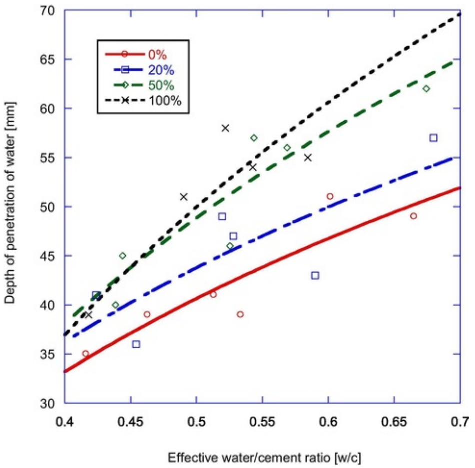

Fig. 7 Water deep penetration of recycled concretes with 28 days cured into marine environment.

3.6 Oxygen permeability

Fig. 8 shows the oxygen permeability of the concretes cured in a marine environment. The results show a tendency to converge for low w/c ratios. Also, the results show that the oxygen permeability for a w/c ratio of 0.4 is around $2{\cdot}10^{-17}\,m^2$ and $3{\cdot}10^{-17}\,m^2$ for the 0% and 100% replacement, respectively. By contrast, for high w/c ratios higher values are recorded. The oxygen permeability coefficient increases to $4{\cdot}10^{-17}\,m^2$ and $6{\cdot}10^{-17}\,m^2$ for the 0% and 100% replacement respectively if the w/c is 0.55. The reductions found in the literature [31] can be attributed to the lower effective w/c ratio of RC concretes with respect to the CC concrete. Medina et al. [32] reported a non negative effect of a reduction in the w/c on concrete oxygen permeability using recycled ceramic sanitary ware aggregate. The results have shown that the permeability (to oxygen and water) behaviour is similar for the concrete cured in a marine environment.

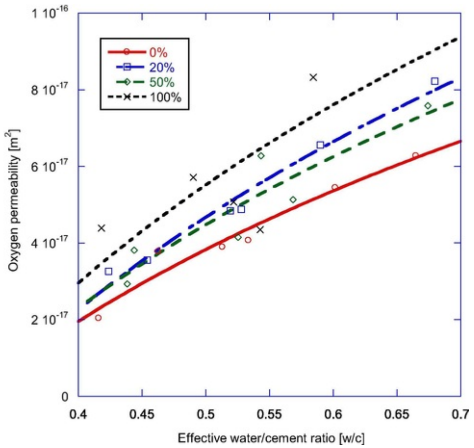

Fig. 8 Oxygen permeability of recycled concretes with 28 days cured into marine environment.

3.7 Accelerated chloride penetration

As shown in the chloride concentration profiles, see Fig. 9, the highest ion concentration was on the exposed outer surface of the concrete and declined sharply in the first 5 mm. The measured chloride ion concentration is below 0.5%wt at 5 mm depth for the CC, 7 mm for the 20% substitution concrete and 12 and 13 mm for the 50% and 100% RC, respectively. The chloride penetration was slightly higher in the concretes containing recycled aggregate than in the control concretes.

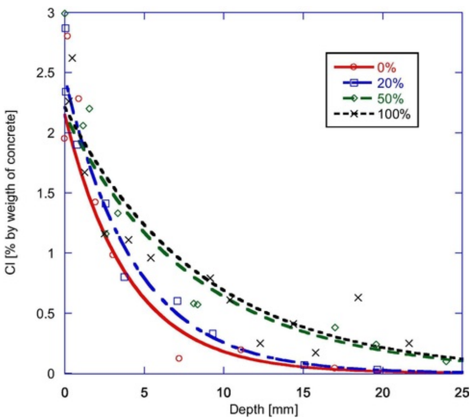

Fig. 9 Cl weight detected in the cement paste vs. the depth from the exposed outermost surface.

These findings were consistent with previous reports on higher chloride penetration (14% greater than in conventional concretes) in concretes in which natural aggregate was replaced by construction and demolition waste aggregate [3,33]. The rise observed here was due to the effect of the addition of RA on total and capillary porosity; as can be observed in Figs. 10 and 11 the CC and RC show a closed cement paste. Similar results were observed by Moon et al. [34] and [3].

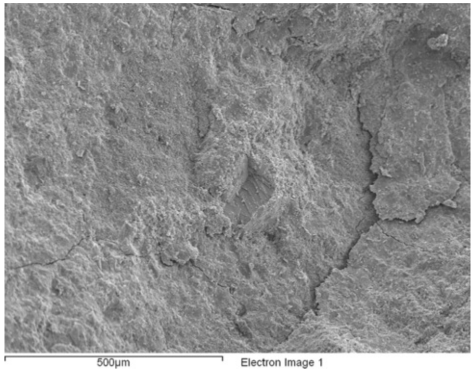

Fig. 10 Micrograph of a RC-DA-0,50-0% tested sample microstructure.

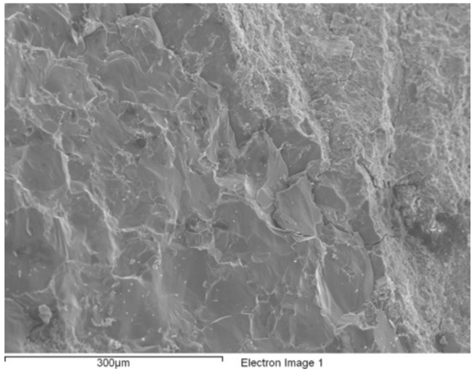

Fig. 11 Micrograph of a RC-DA-0,50–100% tested sample microstructure.

As a curiosity, a rare formation of tin whiskers, observed after exposure to salt fog, is shown in Figs. 12 and 13. Unlike what usually occurs, in this case NaCl has grown not in the form of conventional cubic crystals but in a different structure. This structure was first detected in 1981 by Antiphon, a radio and phone manufacturer in Switzerland, detecting a high level of short-circuits on coated receptacle adapters [35]. 27 years later, after the reports of the NASA Tin Whisker Homepage (http://nepp.nasa.gov/whisker), P. Fontana and R. Pock used a scanning electron microscope (SEM) to observe the same sample again [36].

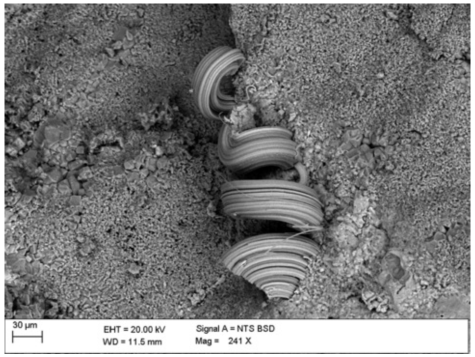

Fig. 12 Micrograph of tin whiskers found into a tested sample after salt fog exposure.

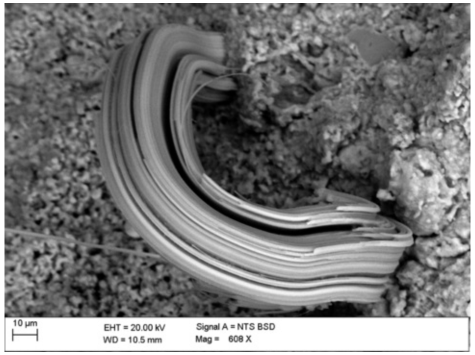

Fig. 13 Detail of a tin whisker found into a tested sample after salt fog exposure.

4 Conclusions

There is a negative effect on durability of the concretes exposed to the marine environment due to the worse curing conditions as compared with the standard environment. The effect of the reduction in durability and mechanical properties is more significant for the high cement content concretes.

The control and recycled concretes with high w/c ratios present similar properties comparing standard and marine environments. The observed loss of properties in low w/c ratio recycled concretes is higher in terms of mechanical properties than for the durability properties.

Marine environment curing conditions affect the concrete in two different ways. On the one hand, the reduction in the temperatures and humidity percentage affects the capability of hydration of the cement. The concretes with low w/c ratios (higher content of cement) are more sensitive to this environment. On the other hand, the more permeable aggregate used for high rate substitution recycled concrete affects the durability more than the mechanical properties. However, substitutions of 20% in weight of the natural coarse aggregate provide similar values to that of the control concrete.

It can be concluded that recycled concrete offers a good behaviour against the agents of the marine environment, such as chlorine. The losses of mechanical properties and durability due to the use of recycled aggregates in the marine environment are lower than those reported in an ideal curing environment. Due to the worse curing conditions, the high cement content control concrete properties are lower than in the case of the recycled concrete.

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The authors declare that they have no conflict of interest.

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Highlights

- ~~The physical and mechanical properties of the concrete cured in a h~~Humidity chamber and ~~in an atmospheric~~ marine environment ~~differ depending on the parameter~~ have been analysed.
- **Higher durability reduction for low w/c ratio than for mechanical propierties.** ~~There is a n~~Negative effect on durability due to the ~~exposure to the marine environment due to the~~ worst curing conditions.
- ~~The~~ Higher durability reduction ~~in the durability properties~~ ~~due to the marine environment for low w/c ratio concretes is higher~~ than for the mechanical properties.
- T~~he reduction in the t~~emperatures and humidity ~~percentage~~ affects ~~the capability of hydration of the cement and the recycled concrete affects~~ more the durability than the mechanical properties.

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Answer: New Highlights (attached): ► Humidity chamber and marine environment have been analysed.
► Negative effect on durability due to the worst curing conditions.
► Higher durability reduction for low w/c ratio than for the mechanical properties.
► Temperatures and humidity affect more the durability than the mechanical properties.
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