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Durability performance of concrete with recycled aggregates from construction and demolition waste plants

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HIGHLIGHTS

- Concrete with fine and coarse recycled aggregates (RA) from construction and demolition waste (CDW).
- CDW from five recycling plants with a wide variety of compositions.
- Analysis of the influence of the RA's source, composition, size and incorporation ratio.
- Analysis of the feasibility of the use of these RA in terms of concrete's durability performance.

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ABSTRACT

This research intends to analyse the durability performance of concrete with recycled aggregates (RA) from construction and demolition waste (CDW) from various locations in Portugal. To that effect water absorption by immersion and capillarity, carbonation resistance and chloride ion penetration resistance tests were performed.

To better understand the experimental results, the characteristics of the various aggregates (natural and recycled) used in the production of concrete were analysed in detail. The composition of the RA was determined and various physical tests of the aggregates were performed. 33 concrete mixes with RA from different CDW recycling plants were evaluated in order to understand the influence that the RA's collection point, and therefore their composition, has on the characteristics of the concrete mixes produced. Both coarse and fine RA were used to determine the influence of their size on concrete's performance.

The analysis of the durability performance allowed concluding that the use of RA is highly detrimental. This is mostly true when fine RA are used. The carbonation resistance is the property most affected by the use of RA, leading to increases in the carbonation depth between 22.2% and 182.4% for the various RA types. However, the most influencing factor is by far the RA's composition.

1. Introduction

The construction industry is one of the greatest and most active sectors in Europe. The weight of this activity is also reflected on the environment. The construction sector consumes more raw materials and energy than any other economic activity and generates the greatest waste fraction within the European Union (EU). Every year around 3000 million tonnes of wastes are produced in the EU. The construction industry in the EU generates around 900 million tonnes of waste per year [1].

Therefore, recycling this waste is fundamental to reduce the volume of dumped waste. On the other hand, recycling has another environmental advantage, that of decreasing the consumption of natural resources. CDW recycling plants have been proved to be economically viable [2,3] as well as having a positive environmental impact [4,5]. However, for that to be true it is essential that the output from the plants can be absorbed by the market. In other words, there is a strong need to diversify the industrial applications of CDW.

One of the ways of recycling under evaluation is using this waste in concrete production, for which CDW have a great potential.

Unfortunately, nowadays most of these waste products are not reintroduced into the construction sector as aggregates for concrete production, one of the few options that do not use the materials for a less demanding function than the original one (thus avoiding downcycling). One of the main reasons for this fact is the

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absence or conservative stance of regulations that would allow for the use of recycled aggregates in concrete production [6].

Several researches have been implemented recently with the goal of evaluating the use in concrete of ceramic materials [7], concrete [8], glass [9], plastics [10], among others. However, studies on concrete with CDW from recycling plants are still scarce. Most previous researches analysed the use of a single type of RA from CDW and did not compare the effect of CDW with different compositions. On the other hand, there are but few studies that exhaustively analyse the RA used in concrete through the analysis of their composition and physical and chemical tests. Knowing the properties of the RA is fundamental to analyse the results of the concrete tests. It is stressed that researches where fine RA from CDW were used are even scarcer. Furthermore, most of these studies are focused on the mechanical performance. In sum, the existing knowledge on the durability performance of concrete with fine CDW RA is in fact very limited.

In this research it was intended to study the aspects mentioned above. CDW from five recycling plants, located in various regions in Portugal, representative of the variety of CDW compositions in industrialised countries, were collected. The RA's composition was then analysed and the aggregates were subjected to several physical and chemical tests. These tests intend to reach a detailed knowledge of the characteristics of the various aggregates (natural and recycled) used in concrete production. To evaluate the durability performance of concrete, absorption by immersion and capillarity, carbonation resistance and chloride ion penetration resistance tests were performed.

The influence of the RA's source, and therefore of their composition, on the durability of the concrete mixes produced was analysed. Five types of coarse CDW and three types of fine CDW were collected, with the objective of analysing the influence of the CDW RA's size on concrete's durability.

2. Literature review

Concrete's water absorption may be measured through immersion and capillarity tests, among others. The first ones fundamentally measure the open porosity, while the second ones measure the capillary absorption resulting from the pressure differential between free surface of the liquids on concrete's face and the free surface on concrete's capillaries. According to Coutinho [11], the smaller the diameter of the pores in concrete the greater its absorption by capillarity is.

Wainwright et al. [12] studied the water absorption by immersion of concrete with fine and coarse RA from crushed concrete. They observed that the quality of the concrete from which the RA are sourced seems to influence the porosity more than the target strength of the resulting concrete.

Matias et al. [13] determined the water absorption by immersion of concrete with full replacement of coarse natural aggregates (NA) with coarse RA from concrete, and obtained values of 17.5% and 17.2%, according to the type of superplasticizer used. These values are higher than the one for the reference concrete (RC): 13.7%.

Evangelista and de Brito [8] obtained an increase of 45% in water absorption by immersion for full replacement of fine NA with fine RA from concrete. They found that this property varies proportionally with aggregates replacement ratio.

Correia et al. [7] evaluated concrete mixes with 100% of coarse brick RA. The authors obtained an increase of water absorption by immersion of 62% relative to the RC.

Vieira [14] analysed the water absorption by immersion of concrete mixes with fine ceramic RA from bricks and sanitary ware. The author concluded that the full replacement of fine NA caused an increase of 45.2% and 47.0%, for bricks and sanitary ware RA respectively.

Matias et al. [13] checked the influence of the shape of the RA on the water absorption by capillarity of concrete with RA from concrete. The authors observed that the mixes with elongated RA showed increases of around 19% relative to the RC, while the use of rounder RA led only to an increase of 12%.

Correia et al. [7] found an increase of capillary water absorption of 70% relative to the RC when using 100% coarse brick RA.

Figueiredo [15] evaluated the capillary water absorption in concrete mixes with granite RA and with ceramic RA, reaching increases of 37% and 146% respectively, for full replacement of the NA. Thus this author proves that there is a great variation of concrete performance in terms of this property according to the RA's composition.

Vieira [14] observed that the capillary water absorption decreased 30.9% with full replacement of fine NA with fine brick RA. The author refers that these results were unexpected, given the greater porosity of the brick RA and the higher total water/cement (w/c) ratio used. However, because the brick RA contain silica, they may have pozzolanic properties, decreasing their permeability to chloride ions. On the other hand, the author concluded that the use of 100% of fine sanitary ware RA caused a 37.6% increase of the capillary water absorption.

Zaharieva et al. [16] evaluated the capillary water absorption of concrete with fine and coarse RA from a CDW recycling plant. The authors maintained the slump in all the mixes and found that full replacement of coarse NA with coarse RA increased this property by 16%. On the other hand, integral replacement of the NA (fine and coarse) caused an increase of capillary water absorption of 42%.

One of the functions of concrete is to protect the steel reinforcement in order to prevent its corrosion. Therefore, determining the carbonation resistance is fundamental to check the concrete durability and its capacity to keep the reinforcement depassivated.

Evangelista and de Brito [8] evaluated the carbonation depth of concrete with fine RA from concrete and obtained a maximum increase of 65% relative to RC, corresponding to full replacement of the fine NA.

Medina et al. [17] evaluated the carbonation resistance of concrete with sanitary ware ceramic RA. The authors found a slight increase of carbonation resistance (up to 3%) for coarse aggregates replacement ratios up to 25%. The authors justified this trend with the decrease of the volume of pores smaller than 0.067 μm.

Vieira [14] analysed the carbonation resistance of concrete with fine ceramic RA from bricks and sanitary ware. The author concluded that full replacement of the fine RA caused an increase of the carbonation depth of 150.6% and 248.8%, respectively for bricks and sanitary ware RA.

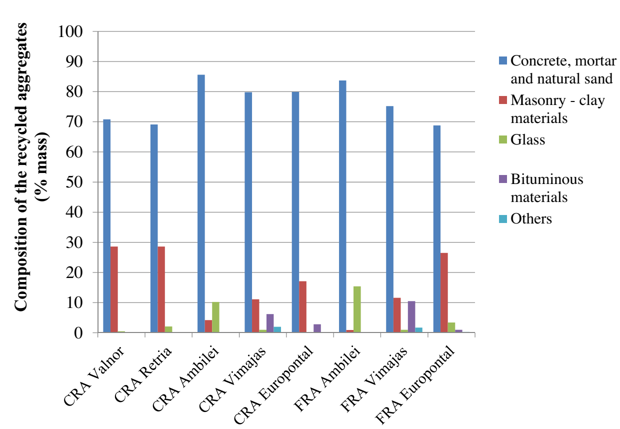

Fig. 1. Composition of the recycled aggregates.

Table 1
Results of the physical tests of the coarse aggregates.

Physical tests	Gravel 2	Gravel 1	"Rice grain"	CRA Valnor	CRA Retria	CRA Ambilei	CRA Vimajas	CRA Europontal
Oven-dry particles density (kg/m^3)	2599	2609	2522	2091	2137	1928	2243	2262
Water absorption (%)	1.5	1.3	2.7	8.6	8.4	9.9	6.4	5.5
Bulk density (kg/m^3)	1360	1350	1348	1095	1236	1288	1261	1285
Shape index (%)	15	17	18	24	24	14	25	21
Los Angeles wear (%)	26	28	–	52	46	44	39	43

Table 2
Results of the physical tests of the fine aggregates.

Physical tests	Oven-dry particles density (kg/m^3)	Water absorption (%)	Bulk density (kg/m^3)
Fine sand	2583	0.3	1530
Coarse sand	2581	0.7	1540
FRA Ambilei	2112	12.9	1435
FRA Vimajas	2070	10.1	1332
FRA Europontal	2063	10.4	1358

Sim and Park [18] investigated the carbonation resistance of recycled aggregate concrete with varying amount of fly ash and recycled aggregate. The concrete evaluated in this study used 100% coarse RA from concrete, various replacement levels of natural aggregate with fine RA from concrete, and several levels of fly ash addition. The measured carbonation depth increased with the addition of fly ash when the replacement level of fine aggregate by RCA was 30% or below. However, this relationship became unclear at the levels of 60% or greater.

Anastasiou et al. [19] also studied the use of fine recycled aggregates in concrete with fly ash and steel slag. The results showed that the use of fine RA from CDW increases concrete's porosity and reduces its durability. However, by using steel slag, the concrete partly recovers the strength and durability loss.

Chlorides penetration is, together with carbonation, the main responsible for depassivation of the reinforcement [20]. Therefore measuring this property through the diffusion coefficient is extremely important to control the service life of the reinforcement within concrete.

Fraaij et al. [21] studied the chloride penetration in concrete mixes with various replacement ratios of fine NA with fine RA from concrete and coarse NA only. The authors found that the depth reached by the chloride ions did not reach 20 mm in all mixes. Therefore, they concluded that the incorporation of RA did not influence concrete's performance in terms of chloride ions permeability.

Evangelista and de Brito [8] concluded that concrete with fine RA from concrete showed lower chloride ions resistance than the RC, due to the greater porosity of the RA.

Table 3
Composition of the reference concrete (RC) (l/l).

Cement		0.115
Fine aggregates	0–0.063	0.000
	0.063–0.125	0.016
	0.125–0.25	0.044
	0.25–0.5	0.050
	0.5–1	0.057
	1–2	0.066
Coarse aggregates	2–4	0.076
	4–5.6	0.041
	5.6–8	0.046
	8–11.2	0.047
	11.2–16	0.121
	16–22.4	0.122
Water		0.182
Voids		0.017
Total		1.000

Torgal and Jalali [22] determined the chloride diffusion coefficient of various mixes with fine ceramic RA. They found that full replacement of the fine NA caused an improvement of this property by around 30%, relative to the RC. This was justified by the hypothetically pozzolanic nature of this material.

Vieira [14] analysed the chloride penetration resistance of concrete with fine ceramic RA for bricks and sanitary ware and concluded that full replacement of the fine NA with brick RA caused an improvement of this property of 56.9%. On the contrary, the use of 100% of sanitary ware RA caused a decrease of this property of 38.2%.

Olorunsogo and Padayachee [23] evaluated the conductivity to chlorides of concrete with coarse RA from CDW containing 84.5% of concrete, after 3, 7, 28 and 56 days of curing. The results indicate that curing time benefits more conventional concrete than the mixes with RA.

Kou et al. [24] investigated the chlorides penetration resistance of concrete with coarse RA from CDW, at 0%, 20%, 50% and 100% of the overall mass of coarse aggregates. The authors found that the chloride ions penetration at 29 and 90 days, in mixes with full replacement of the coarse NA, increases 53% and 47% respectively.

Kou and Poon [25] studied the fresh and hardened properties of self-compacting concrete using coarse and fine recycled concrete aggregates. Three series of self-compacting concrete mixes were prepared with 100% coarse recycled aggregates, and different levels of fine recycled aggregates were used to replace river sand. The chloride ions penetration resistance of the mixes increased as the fine recycled aggregate content increased.

Berndt [26] investigated the replacement of 50% of cement by ground granulated blast furnace slag (GGBS) and fly ash in concrete with RA of concrete. The author noted that the chloride diffusion coefficient was improved by the incorporation of slag in the mix. Contrarily, concrete with 50% fly ash had a relatively poor performance. This result is in conflict with other results for fly ash-modified concrete [27].

Corinaldesi and Moriconi [28] studied the use of additions of fly ash and silica fume in concrete with RA. The RA used in this research were made of 70% of concrete and 27% of ceramics. The results show that it is possible to improve the carbonation and chloride ions penetration resistance in concretes with 100% RA with the incorporation of fly ash, silica fume and superplasticizers.

3. Experimental program

3.1. Tests

In this experimental campaign, the first step was to examine in detail all the aggregates used in the production of concrete. EN 12620:2008 "aggregates for concrete" specifies the properties required from the natural aggregates, those processed mechanically, the recycled aggregates and mixtures of the previous ones, to be used in concrete. This standard applies to aggregates with a dry particles density higher than 2000 kg/m^3, to be used in every concrete type, including those conforming to NP EN 206-1:2013.

The physical characterisation of the aggregates included measuring their particles density and water absorption (according to NP EN 1097-6 and the Rodrigues et al. [29] patent), bulk density and voids volume (according to NP EN 1097-3), shape index (according to NP EN 933-4) and fragmentation resistance according to the Los Angeles method (according to NP EN 1097-2). The following chemical properties were also measured, according to NP EN 1744-1: water soluble chlorides

Table 4
Water absorption by immersion.

	Aggregates replacement ratio (%)								
	0	10		25		50		100	
	Water absorption by immersion (%)	Water absorption by immersion (%)	Δ (%)	Water absorption by immersion (%)	Δ (%)	Water absorption by immersion (%)	Δ (%)	Water absorption by immersion (%)	Δ (%)
CRA Valnor	12.9 ± 0.3	12.7 ± 0.1	−1.7	13.6 ± 0.3	5.2	15.6 ± 0.3	20.6	19.7 ± 0.3	52.9
CRA Vimajas	12.2 ± 0.2	−5.1	12.2 ± 0.3	−5.1	13.0 ± 1.1	0.9	15.0 ± 0.5	16.5	
FRA Vimajas	12.9 ± 0.2	−0.2	15.5 ± 0.3	20.3	17.5 ± 0.5	35.6	21.8 ± 0.2	68.9	
CRA Ambilei	13.7 ± 0.1	6.4	12.8 ± 0.3	−0.8	13.8 ± 0.4	7.0	15.8 ± 0.3	22.8	
FRA Ambilei	13.6 ± 0.3	5.2	14.4 ± 0.4	12.0	14.6 ± 0.5	13.2	18.9 ± 0.4	46.9	
CRA Europontal	12.4 ± 0.2	−3.6	13.2 ± 0.2	2.5	13.5 ± 0.3	4.8	17.2 ± 0.2	33.6	
FRA Europontal	14.0 ± 0.6	8.9	14.8 ± 0.2	15.0	16.1 ± 0.4	24.7	21.2 ± 0.2	64.3	
CRA Retria	12.6 ± 0.2	−2.4	15.3 ± 0.3	18.5	15.4 ± 0.5	19.3	18.4 ± 0.5	42.9	

content, water soluble sulphates content, acid soluble sulphates content, overall sulphur content, light contaminants content, humus content, and water solubility. Finally, the composition of all recycled aggregates was analysed.

In order to characterise the durability performance of concrete with RA from CDW various tests were performed. In the fresh state, the slump test using the Abrams cone, based on EN 12350-2 (2002), and the density test, according to EN 12350-6 (2002), were performed. The characterisation of the hardened concrete was made by measuring the following properties: water absorption by immersion (according to LNEC E-394, 1993), water absorption by capillarity (according to LNEC E-393, 1993), carbonation resistance (according to LNEC E-391, 1993) and chloride ions penetration resistance (according to LNEC E-463, 2004).

3.2. Materials

This research used NA (limestone gravel and alluvial rolled sand) and RA from five Portuguese CDW recycling plants (Valnor, Vimajas, Ambilei, Europontal and Retria). In three of those (Vimajas, Ambilei and Europontal) both coarse and fine RA were collected while in the remaining ones only coarse RA were collected. Cement CEM I 42.5 R and tap water were used in the production of concrete.

The composition of all RA was analysed and they were also subjected to various physical and chemical tests, in order to better explain the performance of concrete made with them.

Fig. 1 shows the results of the visual analysis of the RA's composition. They have a content of "concrete, mortar and natural sand" between 68% and 86%, i.e., this is the main constituent of all RA used. The content of "masonry-clay materials" significantly varies (between 1% and 29%).

Tables 1 and 2 present the results of the characterisation tests of the physical properties of the various aggregates used. Relative to the NA, the RA had lower particles density and much higher water absorption. This is explained by the nature and porosity of the RA. These results demonstrate the need of more mixing water content when using RA. The water absorption of the fine RA (FRA) by comparison with that of the coarse RA (CRA) is highlighted. To determine the water absorption of the fine RA the method defined in the patent of Rodrigues et al. [29] was used.

Because of their more porous nature and rougher shape, the RA also have lower bulk density than the NA. The low bulk density of the CRA from Valnor is highlighted, caused by their high content of clay materials.

With the exception of the aggregates from Ambilei, all the RA have a higher shape index than the NA, which may lead to lower workability of the mixes with RA, relative to the RC.

It was also found that the RA have higher fragmentation level than the NA, possibly due to their composition.

The results from the chemical tests of the RA are presented in Bravo et al. [30], showing that, apart from light contaminants content and water soluble chlorides for a single sample, all the samples comply with EN 12620 limits. Rodrigues et al. [31] made a chemical analysis of eight types of RA from CDW recycling plants and reached the same conclusion. They obtained very high light contaminants contents (between 0.3% and 17.1%).

3.3. Mixes design

33 concrete mixes were produced for this research. Besides a reference concrete (RC), mixes with 10%, 25%, 50% and 100% of the overall volume of coarse NA replaced by CRA (from five different sources) and with 10%, 25%, 50% and 100% of the overall volume of fine NA replaced by FRA (from Vimajas, Europontal and Ambilei only) were produced.

The maximum particles size was 22.4 mm. The particles up to 4 mm were considered fine aggregates and the remaining ones coarse aggregates.

The replacement of NA with RA was made in volume for each size fraction, in order to keep constant in all mixes the aggregates size distribution of the RC. No admixtures and additions were used in this research.

The RC's composition was determined by the Faury's method for the target strength class C30/37. Table 3 shows all materials' volumetric proportions.

All the mixes complied with the 125 ± 15 mm slump range, for better comparison purposes. In a preliminary stage the water content of each mix was adjusted in order to comply with this criterion.

The effective w/c ratio increases as the RA's incorporation grows. However, this trend is not homogenous within the families of mixes with RA as a result of the changes in the RA's composition [30]. There was a significant increase of the effective w/c ratio of the mixes with FRA from Vimajas and Europontal due to the high clay content of these RA, as previously observed by Rodrigues et al. [31]. These fine particles adsorb great amounts of water provoking the need of increasing the w/c ratio to maintain the slump of these mixes. The fresh-state density of the mixes produced decreases as the RA's incorporation ratio increases, as a result of the lower particles density of the RA relative to the NA [30].

4. Results and discussion

4.1. Water absorption by immersion

The water absorption by immersion test allows evaluating the open pores within concrete. They are mostly due to the pores within the aggregates, the air that remains after the components' mix and the mixing water content above the one strictly necessary for cement hydration.

The results from the test for all the mixes, as well as their variation relative to the RC (Δ), are presented in Table 4.

The results from Table 4, represented graphically in Fig. 2, allow concluding that the replacement of NA with RA caused an increase of the water absorption by immersion. This can be partly justified by the effective w/c ratio of the mixes with RA, needed to keep the slump constant in all mixes. On the other hand, the greater water absorption of the RA relative to the NA may have contributed to increase the water absorption of concrete. Most of RA analysed here contain materials with high water absorption capacity (e.g. ceramic materials).

Oliveira et al. [32] determined the water absorption by immersion of concrete with coarse RA from CDW made mostly of concrete. All the mixes were produced in order to have a compressive strength of 27 MPa. For full replacement, the authors found that the water absorption by immersion increased between 5.5% and 14.2%.

Fig. 2 shows that the water absorption by immersion increased substantially as the size of the replaced aggregates decreased. The results of the mixes with 25% of CRA were similar to that of the RC, meaning that the property is unaffected by this level of incorporation of CRA. This lack of influence was limited to 10%, when fine aggregates were replaced. Wainwright et al. [12] studied the water absorption by immersion of concrete mixes with fine and coarse RA from concrete. They concluded that the incorporation of fine RA is more detrimental than that of coarse RA.

The source of the RA used also influenced the water absorption by immersion. Because the RA were collected in different plants in

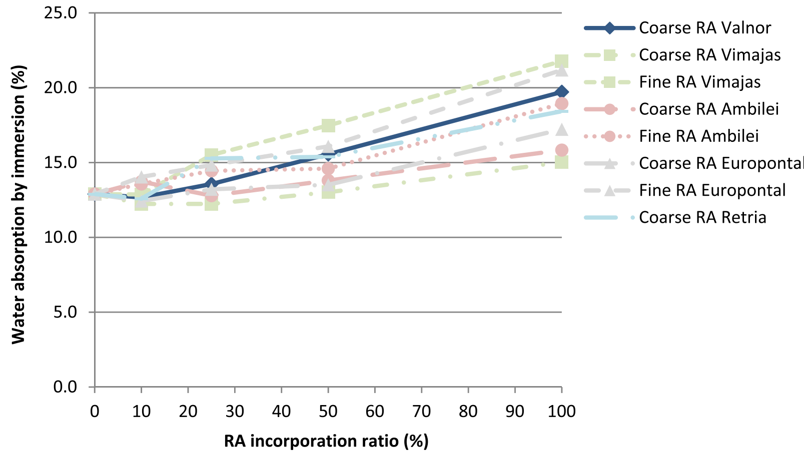

Fig. 2. Water absorption by immersion.

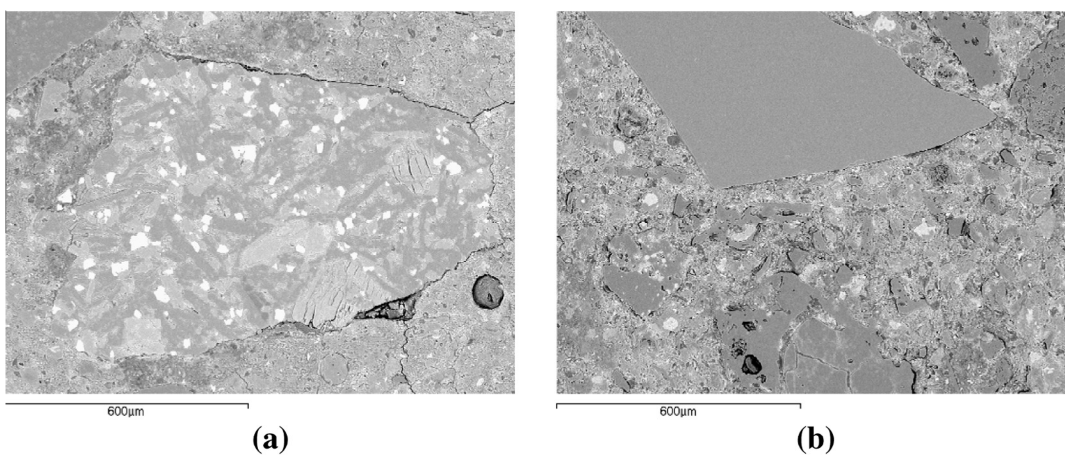

Fig. 3. Comparison of the micro-porosity of the concrete mixes with fine RA: (a) detail of the ITZ of the mix with FRA from Vimajas; (b) detail of the ITZ of the mix with FRA from Ambilei.

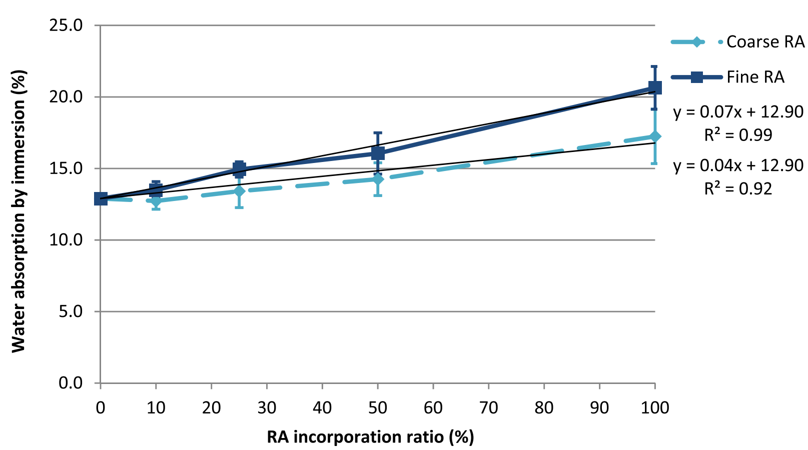

Fig. 4. Water absorption by immersion versus aggregates' replacement ratio.

several Portuguese locations, their composition varies significantly. This was demonstrated in the analysis of the RA's composition summarized in Fig. 1. Therefore, as expected, the tests results also varied a lot. In the mixes with 100% of CRA from Ambilei there was an increase of 22.8% of the water absorption by immersion, while in the mixes with 100% of RA from Valnor the increase reached 52.9%. In terms of the mixes with CRA, those from Valnor, Europontal and Retria led to the highest increase of water absorption by immersion, which is justified by the high content of ceramics in the RA of these recycling plants (between 17.1% and 28.6%). In the mixes with FRA the increase of water absorption by immersion was much higher when RA from Vimajas and Europontal were used (68.9% and 64.3% respectively), than for RA from Ambilei (46.9%). This is explained by the much higher effective w/c ratio

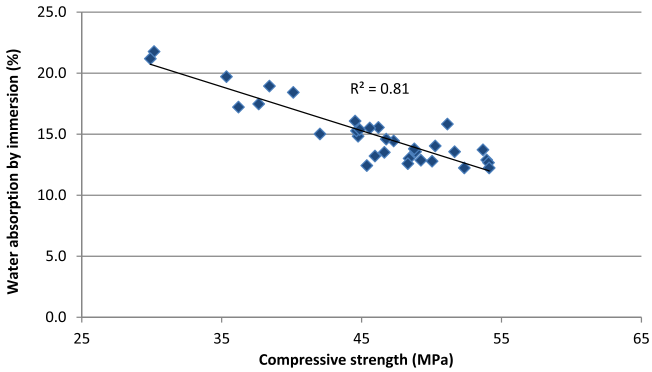

Fig. 5. Water absorption by immersion versus compressive strength.

of these mixes, which was due to the presence of clay in the RA [31]. These fine particles coat the RA grains and adsorb mixing water, besides hindering the adequate bond between these RA and the cement paste and weakening the concrete's inner structure.

Using scanning electron microscopy (SEM), it was found that these phenomena caused an increase of porosity of these mixes, leading to the increase in water absorption by immersion. Fig. 3 shows that the mixes with FRA from Vimajas have higher porosity than those with FRA from Ambilei. The results of the mixes with FRA from Europontal may also be explained by the high content of ceramic materials of these RA (26.5%).

Fig. 4 shows that the water absorption by immersion grows linearly with the replacement ratio of NA with RA, as proved by the high values of the determination coefficient (0.92 and 0.99, for the mixes with CRA and FRA respectively). On the other hand, Fig. 4 equally proves that the water absorption by immersion increases as the size of the aggregates replaced decreases.

Besides analysing the durability performance of concrete mixes with CDW RA, this experimental research also determined the mechanical performance of those mixes [30]. Fig. 5 shows there is a linear relationship between the water absorption by immersion and the compressive strength of these mixes, as proved by the high determination coefficient (0.81) of the linear regression. Ferreira [20] developed a study in which he also concluded there is a linear relationship between these properties.

4.2. Water absorption by capillarity

The absorption by capillarity consists on the penetration into concrete of a fluid, through the action of pressure gradients. This occurs when the liquid contacts the pores and is caused by capillary forces, which increase as the pores' diameter decreases.

Table 5 shows the capillary water absorption results after 72 h of contact between the water and one of the surfaces of the concrete specimen. The value increases as the substitution ratio of NA with RA grows. This is essentially due to the increase of the effective w/c ratio and greater porosity of the mixes with RA.

Fig. 6 represents graphically the results from Table 5. It shows that the size of the replaced aggregates has great influence on the increase of capillary water absorption. The mixes with FRA have much higher absorption values than those with CRA. These results confirm the conclusions drawn by Zaharieva et al. [16].

As seen in Table 5, the incorporation of 10% of RA caused a decrease of the capillary water absorption in almost all the mixes evaluated. The exceptions are the mixes with 10% of CRA from Valnor and Europontal, which had an insignificant increase of this property (3.3% and 0.3%, respectively), relative to the RC. This improvement can be explained by the filler effect. The filler effect

Table 5
Water absorption by capillarity.

	Aggregates replacement ratio (%)								
	0	10		25		50		100	
	Water absorption by capillarity (g/mm²)	Water absorption by capillarity (g/mm²)	Δ (%)	Water absorption by capillarity (g/mm²)	Δ (%)	Water absorption by capillarity (g/mm²)	Δ (%)	Water absorption by capillarity (g/mm²)	Δ (%)
CRA Valnor	2.14E-03 ± 1.45E-04	2.21E-03 ± 1.85E-04	3.3	2.23E-03 ± 4.39E-05	4.4	2.41E-03 ± 1.22E-05	12.5	3.09E-03 ± 1.03E-04	44.6
CRA Vimajas		1.76E-03 ± 7.51E-05	−17.8	2.61E-03 ± 9.50E-05	22.2	2.74E-03 ± 3.28E-05	28.2	2.77E-03 ± 8.21E-05	29.6
FRA Vimajas		1.91E-03 ± 5.11E-05	−10.4	3.06E-03 ± 1.43E-04	43.2	3.34E-03 ± 4.98E-05	56.1	3.99E-03 ± 8.56E-05	86.7
CRA Ambilei		1.97E-03 ± 3.34E-05	−7.7	2.06E-03 ± 1.47E-04	−3.4	2.05E-03 ± 8.78E-05	−3.9	3.02E-03 ± 2.87E-04	41.2
FRA Ambilei		1.89E-03 ± 4.00E-05	−11.6	2.27E-03 ± 4.81E-05	6.3	2.62E-03 ± 2.82E-05	22.7	3.18E-03 ± 2.72E-04	48.8
CRA Europontal		2.14E-03 ± 5.64E-05	0.3	2.01E-03 ± 7.75–05	−6.3	2.17E-03 ± 7.67E-05	1.3	3.06E-03 ± 6.46E-05	43.1
FRA Europontal		1.79E-03 ± 6.36E-05	−16.1	1.99E-03 ± 1.22E-04	−6.8	2.24E-03 ± 2.91E-04	4.6	3.96E-03 ± 2.30E-04	85.1
CRA Retria		1.99E-03 ± 1.09E-04	−6.7	2.15E-03 ± 2.71E-05	0.5	2.36E-03 ± 1.59E-05	10.3	2.39E-03 ± 2.51E-05	11.8

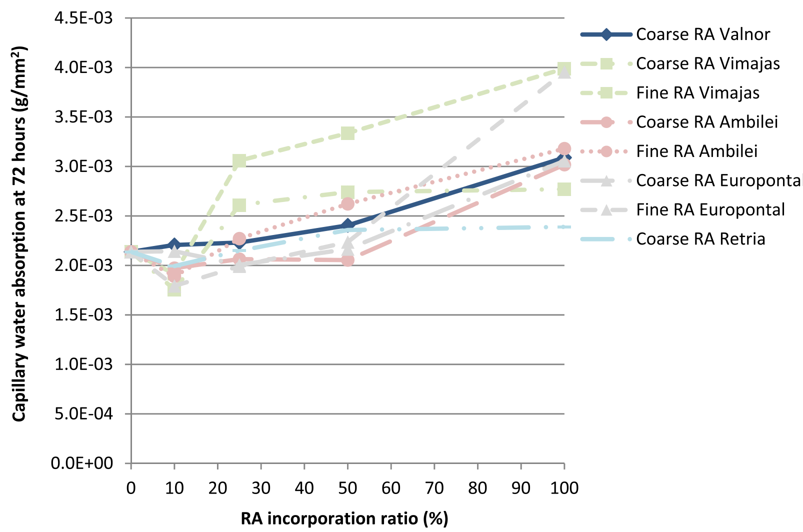

Fig. 6. Water absorption by capillarity.

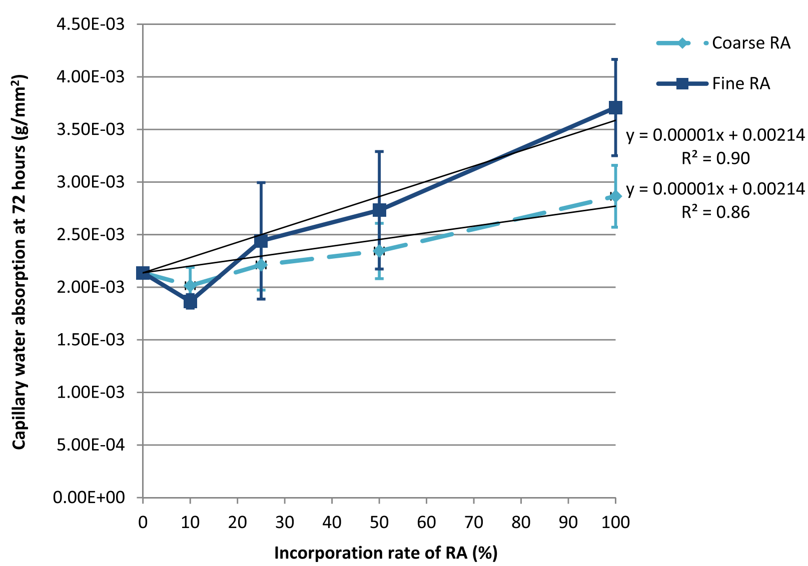

Fig. 7. Water absorption by capillarity versus aggregates' replacement ratio.

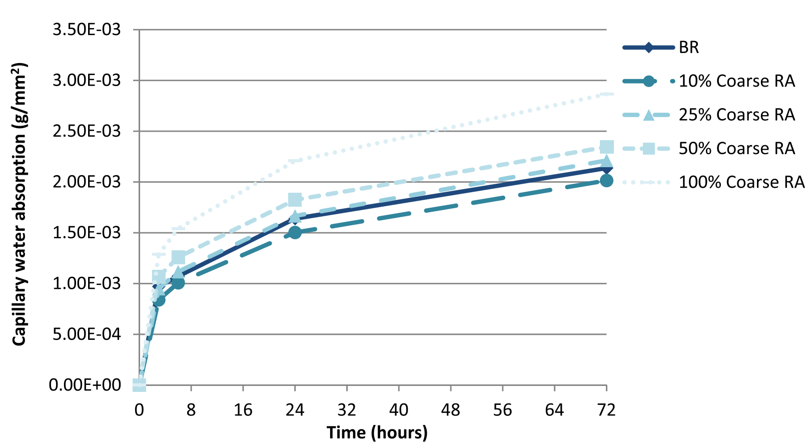

Fig. 8. Water absorption by capillarity over time of the mixes with coarse RA.

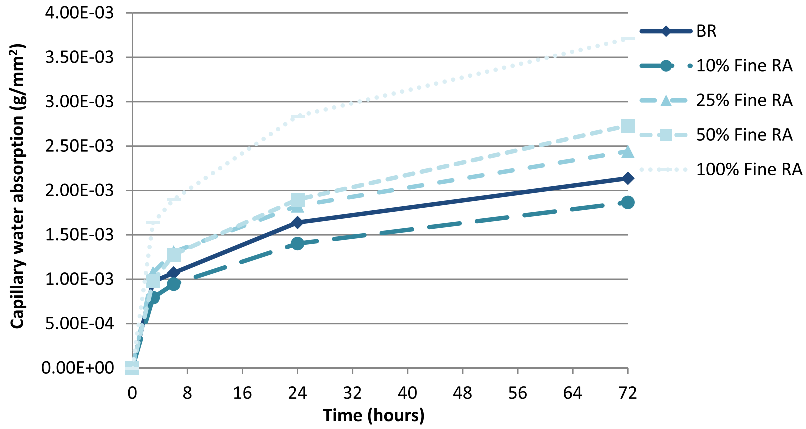

Fig. 9. Water absorption by capillarity over time of the mixes with fine RA.

is defined as proper arrangement of small particles into the microstructure of concrete that fill the voids. This effect contributes towards the improvement of the mechanical and durability performance by making the mix more compact. In this research the filler effect is caused by very fine aggregates present in RA. These small particles only improve the concrete's performance for low RA incorporation ratios. After that these particles occupy space previously occupied by other materials decreasing the compactness of the mixes.

Fig. 6 confirms that this property varies considerably with the RA's source. For example, full replacement of the coarse aggregates caused increases of the capillary water absorption between 11.8% and 44.6%, essentially because of differences in the composition of these RA: e.g. the ceramic materials content in the RA varies between 4.2% and 28.6%. On the other hand, full replacement of the fine aggregates caused increases between 48.8% and 86.7%, as a function of the RA's source. This variation is mostly due to two factors: the scatter in ceramic materials content in the FRA (between 0.9% and 26.5%); the high increase of the effective w/c ratio in the mixes with FRA from Vimajas and Europontal, caused by the presence of clay in those RA. These factors led to an increase of the porosity of the mixes with RA from these two plants and consequently a great increase of the capillary water absorption.

Fig. 7 shows the increase of the capillary water absorption as the aggregates replacement ratio grows. The high values of the determination coefficient of the linear regressions performed (0.86 and 0.90 for the mixes with CRA and FRA respectively) prove that this increase is approximately linear. Fig. 7 also shows that the mixes with FRA have much higher absorption values than the mixes with CRA.

Table 6
Carbonation resistance at 7, 28, 56 and 91 days.

	Carbonation resistance at 7 days (mm)	Δ (%)	Carbonation resistance at 28 days (mm)	Δ (%)	Carbonation resistance at 56 days (mm)	Δ (%)	Carbonation resistance at 91 days (mm)	Δ (%)
BR	2.7 ± 0.1	–	4.5 ± 0.4	–	5.2 ± 0.3	–	6.6 ± 0.5	–
C10C-Valnor	2.7 ± 0.2	0.8	5.1 ± 0.2	13.0	7.1 ± 1.0	36.0	7.7 ± 0.5	16.1
C25C-Valnor	3.9 ± 0.3	45.8	5.4 ± 0.3	20.4	9.7 ± 1.2	85.6	9.1 ± 0.7	38.2
C50C-Valnor	3.5 ± 0.1	31.8	5.5 ± 0.2	23.1	9.0 ± 0.3	73.6	8.4 ± 0.6	26.8
C100C-Valnor	5.1 ± 0.6	91.5	9.7 ± 0.2	115.7	12.0 ± 0.9	129.6	14.8 ± 0.5	123.3
C10C-Vimajas	2.8 ± 0.2	4.2	4.4 ± 0.3	−1.9	5.5 ± 0.3	5.4	8.2 ± 0.2	23.7
C25C-Vimajas	2.8 ± 0.4	5.4	5.1 ± 1.0	13.0	5.6 ± 0.3	8.0	8.2 ± 0.3	24.7
C50C-Vimajas	2.9 ± 0.3	7.0	5.2 ± 0.4	15.7	6.5 ± 0.3	25.6	9.5 ± 0.8	44.5
C100C-Vimajas	3.4 ± 0.4	25.6	5.5 ± 0.3	22.2	8.8 ± 0.8	68.8	10.0 ± 0.7	52.1
C10F-Vimajas	3.2 ± 0.2	19.4	5.1 ± 0.4	13.0	6.9 ± 0.3	32.8	9.3 ± 0.7	41.3
C25F-Vimajas	4.0 ± 0.1	47.3	7.0 ± 0.4	56.5	9.7 ± 0.4	85.6	13.8 ± 0.6	109.5
C50F-Vimajas	5.7 ± 0.4	110.9	9.2 ± 0.8	104.6	11.4 ± 0.8	119.2	18.3 ± 0.3	176.3
C100F-Vimajas	6.1 ± 0.4	127.9	12.7 ± 0.9	182.4	17.9 ± 0.5	244.0	24.5 ± 0.1	271.0
C10C-Ambilei	2.8 ± 0.2	4.5	3.8 ± 0.4	−14.8	8.6 ± 0.1	64.8	9.7 ± 0.2	46.4
C25C-Ambilei	2.9 ± 0.3	7.0	5.7 ± 0.3	25.9	8.6 ± 0.6	65.6	10.3 ± 0.5	55.2
C50C-Ambilei	3.1 ± 0.2	16.6	5.8 ± 0.3	29.4	8.7 ± 0.1	66.7	10.3 ± 0.3	55.8
C100C-Ambilei	3.1 ± 0.3	17.1	5.8 ± 0.7	29.4	8.7 ± 0.1	67.0	11.3 ± 0.9	71.7
C10F-Ambilei	4.0 ± 0.3	50.1	6.9 ± 0.4	52.8	10.1 ± 0.3	93.6	10.4 ± 0.4	57.5
C25F-Ambilei	4.1 ± 0.1	51.3	6.9 ± 0.1	52.2	10.1 ± 0.4	94.4	11.1 ± 1.3	68.5
C50F-Ambilei	5.1 ± 0.2	88.2	8.0 ± 0.4	78.7	10.7 ± 0.7	105.6	11.5 ± 0.6	73.5
C100F-Ambilei	5.1 ± 0.2	88.5	11.5 ± 0.3	155.6	14.9 ± 1.3	185.6	17.7 ± 0.9	167.5
C10C-Europontal	1.7 ± 0.3	−36.4	3.3 ± 0.1	−25.9	4.6 ± 0.5	−12.0	4.2 ± 0.8	−36.6
C25C-Europontal	1.6 ± 0.1	−41.1	3.3 ± 0.8	−25.9	5.7 ± 0.3	9.6	5.6 ± 0.9	−15.8
C50C-Europontal	1.6 ± 0.1	−40.9	3.4 ± 1.1	−24.1	5.0 ± 0.1	−5.0	6.1 ± 0.5	−8.3
C100C-Europontal	4.1 ± 0.6	53.5	6.9 ± 0.1	53.3	10.1 ± 0.1	93.3	12.8 ± 1.1	93.7
C10F-Europontal	3.0 ± 0.4	11.6	5.3 ± 0.4	16.7	7.3 ± 0.3	40.0	9.0 ± 0.4	36.9
C25F-Europontal	3.0 ± 0.3	10.1	6.1 ± 0.2	36.1	8.7 ± 0.3	66.4	10.7 ± 1.1	62.1
C50F-Europontal	3.8 ± 0.2	41.1	7.4 ± 1.0	63.9	12.3 ± 0.3	136.0	13.1 ± 1.0	98.7
C100F-Europontal	8.1 ± 0.2	201.0	11.6 ± 0.4	158.3	17.6 ± 0.7	237.3	22.9 ± 0.6	247.0
C10C-Retria	2.4 ± 0.3	−11.6	4.2 ± 0.4	−6.3	6.5 ± 0.5	24.4	7.9 ± 0.3	20.1
C25C-Retria	3.0 ± 0.3	11.6	5.7 ± 0.7	25.9	8.7 ± 0.5	67.5	10.3 ± 0.7	55.2
C50C-Retria	3.0 ± 0.3	12.4	5.6 ± 0.4	25.0	7.7 ± 0.3	47.2	10.3 ± 1.2	55.2
C100C-Retria	3.1 ± 0.3	14.7	8.0 ± 1.1	76.9	12.8 ± 0.7	144.8	13.5 ± 0.6	104.3

Figs. 8 and 9 show that the capillary water absorption of the various mixes occurs more intensely in the first hours of contact of the concrete with water, as expected. They also show that the use of up to 10% of RA causes an improvement in that property.

5. Carbonation resistance

The carbonation process starts with the penetration of carbon dioxide into concrete. In the presence of humidity it reacts with

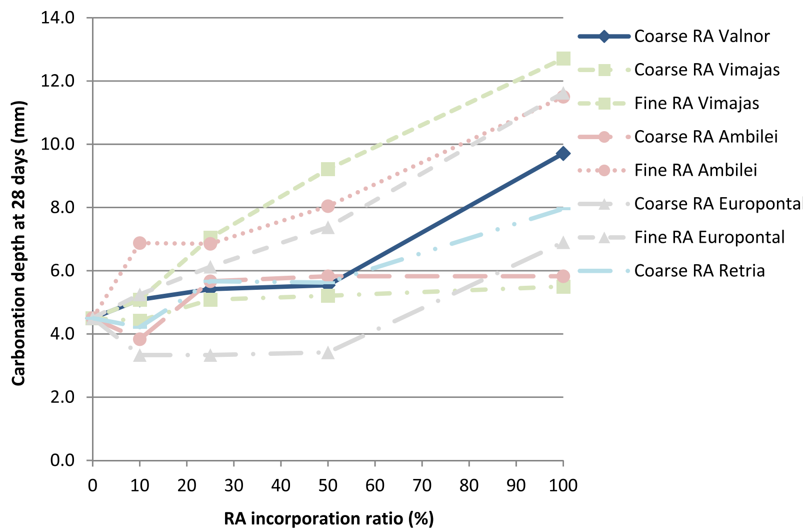

Fig. 10. 28-Day carbonation resistance.

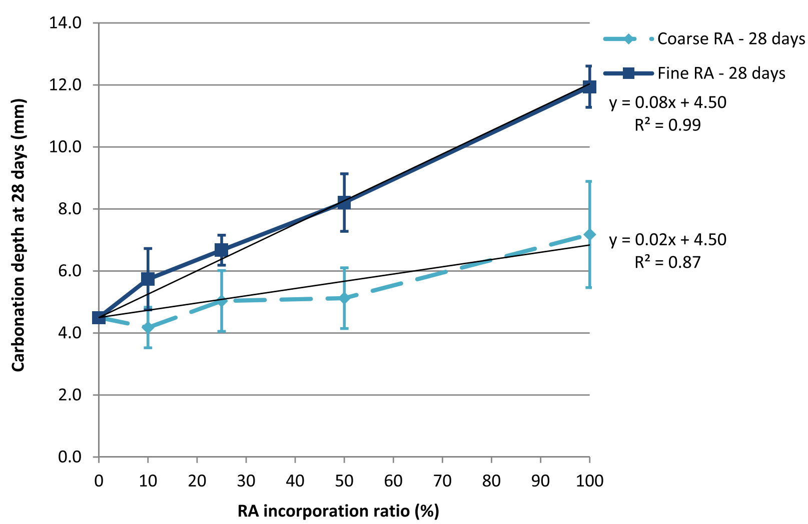

Fig. 11. 28-Day carbonation resistance versus aggregates' replacement ratio.

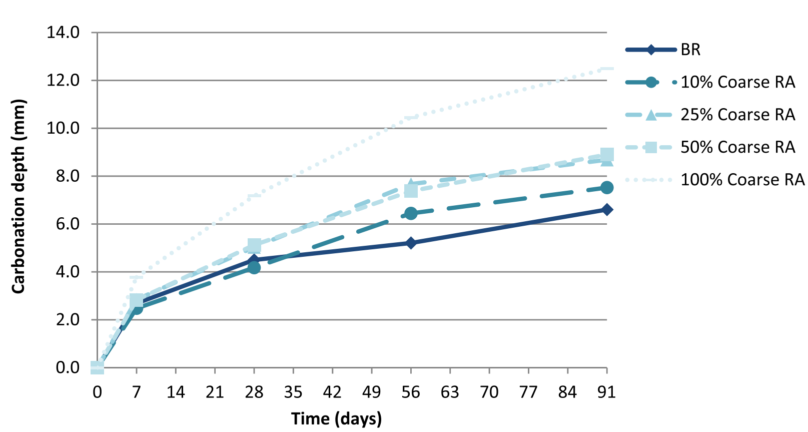

Fig. 12. Carbonation depth over time of the mixes with coarse RA.

the hydrated cement minerals decreasing the alkalinity level. This process proceeds progressively from the outside to the inside.

Table 6 shows the carbonation (front) depth for the various mixes, after 7, 28, 56 and 91 days inside a carbonation chamber.

Table 6 and its representation in Fig. 10 allow concluding that the mixes with RA have lower carbonation resistance than the RC. This was predictable since, when the water absorption was analysed, a property influenced by the same factors, the same trend occurred.

Bodin and Zaharieva [33] also evaluated the carbonation depth in mixes with fine and coarse RA from a CDW recycling plant. They observed that full replacement of the coarse NA caused an increase of the 28-day carbonation depth of 100%. On the other hand, full replacement of the NA (fine and coarse) caused an increase of 190%.

Fig. 10 shows that this increase strongly depends on the type of RA used. The mixes with CRA from Ambilei and Vimajas have a higher carbonation resistance than the remaining mixes with RA. This may be justified by the high ceramics content in the RA from Valnor, Europontal and Retria (between 17.1% and 28.6%). On the other hand, the carbonation depth of the mixes with RA from Vimajas and Europontal was much higher than that of the remaining mixes. This is explained by the much higher effective w/c ratio of these mixes, which was due to the presence of clay in the RA. These fine particles coat the RA grains and adsorb mixing water, besides hindering the adequate bond between these RA and the

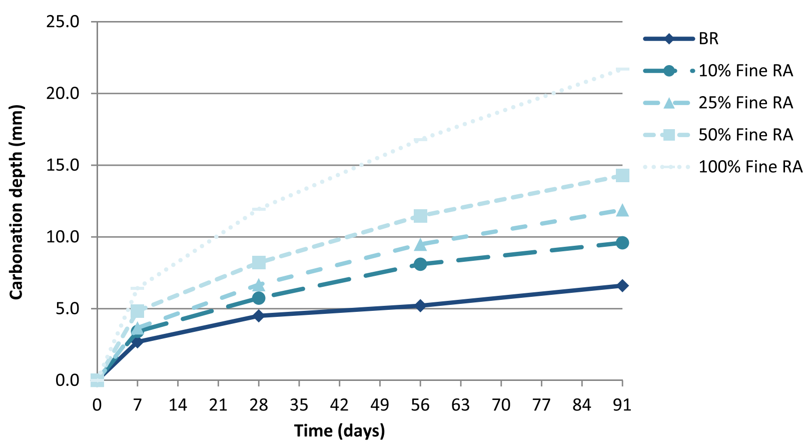

Fig. 13. Carbonation depth over time of the mixes with fine RA.

Table 7
Chloride ion diffusion coefficient at 28 and 91 days.

	Chloride ion diffusion coefficient at 28 days ($\times 10^{-12}$ m^2/s)	Δ (%)	Chloride ion diffusion coefficient at 91 days ($\times 10^{-12}$ m^2/s)	Δ (%)
BR	12.7 ± 1.3	–	12.5 ± 0.0	–
C10C-Valnor	13.7 ± 0.5	8.4	13.1 ± 0.3	4.1
C25C-Valnor	15.8 ± 0.2	24.3	13.0 ± 2.6	3.5
C50C-Valnor	16.1 ± 0.5	26.7	15.2 ± 1.2	21.4
C100C-Valnor	17.1 ± 0.9	34.9	16.8 ± 0.8	34.2
C10C-Vimajas	10.4 ± 1.1	−17.6	12.3 ± 0.5	−1.8
C25C-Vimajas	13.2 ± 1.4	3.9	13.3 ± 1.3	6.4
C50C-Vimajas	13.9 ± 0.7	9.9	14.4 ± 1.4	14.8
C100C-Vimajas	15.7 ± 0.4	24.2	17.1 ± 1.3	36.1
C10F-Vimajas	17.6 ± 1.1	39.1	16.0 ± 0.7	27.6
C25F-Vimajas	18.9 ± 0.8	49.1	17.9 ± 1.2	42.7
C50F-Vimajas	23.9 ± 0.7	88.7	22.9 ± 0.9	82.4
C100F-Vimajas	29.2 ± 1.9	130.0	28.6 ± 2.9	128.0
C10C-Ambilei	13.5 ± 0.4	6.7	12.1 ± 0.4	−3.7
C25C-Ambilei	13.9 ± 0.3	9.6	12.3 ± 0.6	−1.6
C50C-Ambilei	13.9 ± 0.1	9.8	11.9 ± 0.7	−4.8
C100C-Ambilei	14.1 ± 1.0	11.2	12.3 ± 0.6	−1.9
C10F-Ambilei	14.0 ± 1.7	10.3	13.1 ± 0.5	4.2
C25F-Ambilei	14.5 ± 1.2	14.1	13.7 ± 0.6	9.4
C50F-Ambilei	14.4 ± 0.7	13.6	13.5 ± 1.3	7.8
C100F-Ambilei	14.7 ± 0.4	16.0	13.4 ± 0.1	6.6
C10C-Europontal	11.1 ± 1.3	−12.6	12.3 ± 0.3	−1.9
C25C-Europontal	13.9 ± 0.3	9.3	13.4 ± 0.1	6.7
C50C-Europontal	14.6 ± 1.1	14.8	14.3 ± 0.5	14.1
C100C-Europontal	18.4 ± 1.6	45.5	19.1 ± 2.1	52.4
C10F-Europontal	15.6 ± 0.7	23.3	14.6 ± 0.8	16.0
C25F-Europontal	17.7 ± 0.6	39.2	18.2 ± 0.4	45.3
C50F-Europontal	20.5 ± 0.6	61.7	21.2 ± 0.1	69.1
C100F-Europontal	24.3 ± 0.5	92.0	27.7 ± 0.8	120.6
C10C-Retria	14.2 ± 0.8	12.3	14.8 ± 0.4	18.1
C25C-Retria	15.2 ± 0.1	19.8	15.0 ± 0.8	19.7
C50C-Retria	15.9 ± 0.4	25.6	15.6 ± 0.8	24.1
C100C-Retria	17.4 ± 1.3	37.2	16.4 ± 0.9	30.8

cement paste and weakening the concrete's inner structure. These phenomena caused an increase of porosity of these mixes, leading to the increase in carbonation depth.

Gomes and de Brito [34] evaluated the carbonation resistance of mixes with 50% of CRA from concrete, with 25% of ceramic CRA, and with 37.5% of CRA both from concrete and ceramic materials. They found an increase of carbonation depth relative to the RC of 10%, 9% and 30% respectively. This research thus confirms that the use of ceramics RA in concrete is more detrimental to its carbonation resistance than the incorporation of RA from concrete.

Fig. 11 shows there is a significant increase of carbonation depth as the size of the replaced aggregates decreases, a negative trend common to the previous properties. It is due to the increase of effective w/c ratio and the greater clay content in some of the FRA.

Fig. 11 demonstrates that the increase of carbonation depth with the aggregates replacement ratio is linear, as shown by the determination coefficient values of the linear regressions performed (0.87 and 0.99).

Figs. 12 and 13 analyse the evolution of the carbonation depth in the mixes with varying coarse and fine RA contents. As expected, it is found that the progress of the carbonation front is faster in the first 7 days.

5.1. Chloride ions penetration resistance

The transport mechanism of chloride ions inside concrete is complex and may include water diffusion, impregnation and capillary absorption processes. The penetration of chlorides has, together with carbonation, the main responsibility for the depassivation of the reinforcement.

Table 7 and Fig. 14 present the results of this test. They seem to indicate that the use of RA in concrete causes a slight increase of the chloride diffusion coefficient relative to the RC. The only exceptions are the mixes with FRA from Vimajas and Europontal, where there was a significant increase. These trends are justified by the great increase of the w/c ratio in these mixes, in order to have the same slump as the others.

Table 7 also shows that increasing the curing period of the mixes led to a decrease in the penetration of chloride ions. This confirms other authors' findings, i.e. the curing period of the

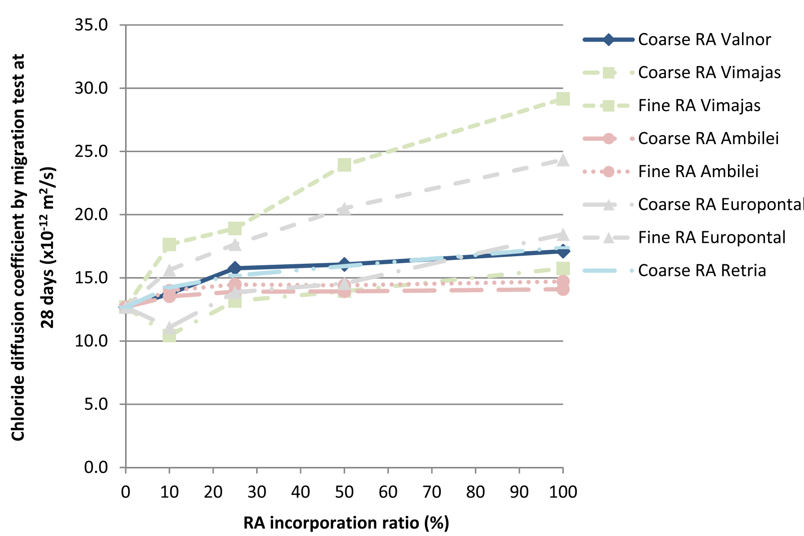

Fig. 14. 28-Day chloride ion diffusion coefficient.

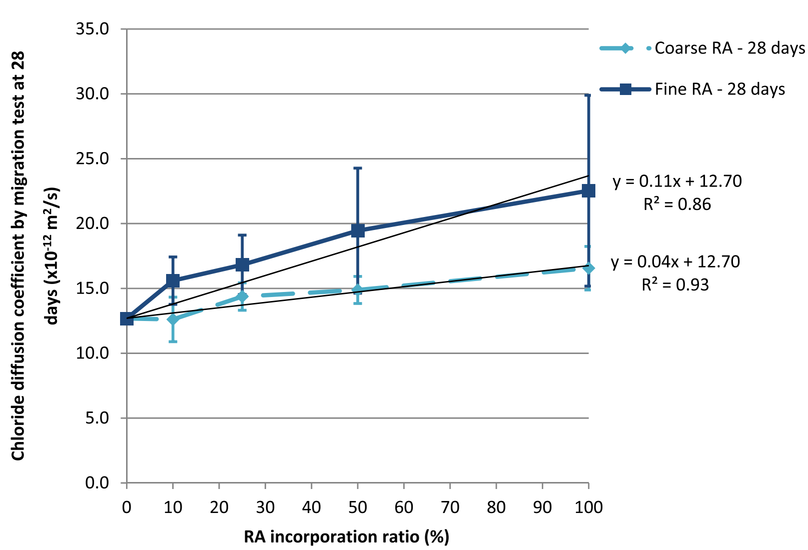

Fig. 15. 28-Day chloride ion diffusion coefficient versus aggregates' replacement ratio.

Table 8
Variation of all concrete durability properties with the incorporation of RA.

Tests	Quantitative variation of the mixes relative to the RC							
	C100C-Valnor	C100C-Vimajas	C100F-Vimajas	C100C-Ambilei	C100F-Ambilei	C100C-Europontal	C100F-Europontal	C100C-Retria
Water absorption by immersion	52.9	16.5	68.9	22.8	46.9	33.6	64.3	42.9
Water absorption by capillarity (at 72 h)	44.6	29.6	86.7	41.2	48.8	43.1	85.1	11.8
Carbonation depth (at 28 days)	115.7	22.2	182.4	29.4	155.6	53.3	158.3	76.9
Chloride ions diffusion coefficient (at 28 days)	34.9	24.2	130.0	11.2	16.0	45.5	92.0	37.2

specimens positively influences the chloride ions penetration resistance.

Just like for the previous properties the replacement of fine aggregates led to chloride diffusion coefficient values higher than those in mixes with CRA. In the mixes with RA from Vimajas and Europontal that trend was explained for the other fluids penetration mechanisms. In the mixes with RA from Ambilei the slight increase of the chloride diffusion coefficient as the size of the replaced aggregates decreased is due to the differences in the composition of the FRA and CRA from that plant. These differences also caused a difference in the water absorption of the mixes made with them (9.9% and 12.9% for the CRA and FRA respectively). However, the results of the tests at 28 and 91 days of the mixes with coarse and fine RA from Ambilei indicate no change of the chloride ions penetration resistance resulting from the use of these RA.

The results from the literature have a wide scatter, as in our study. Fraaij et al. [21] concluded that the RA incorporation does not influence the concrete performance in terms of permeability to chloride ions. On the other hand, Olorunsogo and Padayachee [23] obtained increases of conductivity to chlorides of concrete mixes with coarse RA from CDW with 84.6% concrete content.

Fig. 15 shows that the increment of the chlorides diffusion coefficient varies linearly with replacement ratio of NA with RA, as proved by the values of the determination coefficient of the linear regressions performed (0.93 and 0.86 for the mixes with CRA and FRA respectively).

6. Conclusions

There are various studies that evaluate the mechanical performance of concrete with RA from CDW. With this research the intention was to analyse the durability performance of concrete made with RA from several CDW recycling plants in Portugal, in order to evaluate the influence of the RA's composition on the characteristics of concrete made with them. Five types of RA were collected from coarse CDW (from Valnor, Vimajas, Ambilei, Europontal and Retria plants), as well as three types from fine CDW (from Vimajas, Ambilei and Europontal plants). The collection of coarse and fine RA was meant to analyse as well the influence of the size of the CDW RA on the concrete made with them.

The composition of the various RA used was determined and several physical and chemical tests of the RA were performed. These tests aimed at better understanding the experimental results of the concrete mixes and detected a great variety in the composition of the RA, comprising ceramic materials, concrete, glass, metals, among others.

The results of the fresh-state concrete allowed concluding that, in order to keep the slump constant, it was necessary to increase the effective w/c ratio of some of the mixes as the replacement ratio of NA with RA increased. This occurred mostly when fine RA from Vimajas and Europontal were used. It was also found that the use of RA causes a decrease in concrete's density, which reached values between 4.7% and 7.7% for full replacement of fine and coarse RA.

It is concluded that the use of RA is detrimental to the quality of hardened concrete in terms of its durability. Table 8 presents a summary of all the results, allowing the analysis of the variation of the results of the four properties analysed, for the various mixes with 100% of RA relative to the RC.

There is a great range of results depending on the plant the RA were collected from. This was expected since each RA type has a different composition, depending on the local construction activities. This causes a significant scatter in the characteristics of these aggregates and consequently in the properties of the concrete mixes made with them. In Table 8 the values of the properties that were significantly affected (by more than 50%) by the RA's incorporation were underlined. The mixes with FRA from Vimajas and Europontal presented the worst results, partly because of their great clay content. These fine particles coat the RA grains and inhibit an adequate bond between the RA and the cement paste, weakening the concrete inner structure. Furthermore, clay adsorbs part of the mixing water, which made it necessary to use a greater effective w/c ratio in the mixes with FRA from Vimajas and Europontal, to have the same slump as the other mixes. This is another cause of the worse results of these mixes in terms of concrete durability performance.

It is also concluded that the use of FRA causes a significant drop in concrete quality for all properties analysed, relative to the use of CRA.

Finally the carbonation resistance was the property with the worst results from the use of these RA in concrete. As seen in Table 8, only two of the eight types of CDW RA led to variations in this property lower than 50%.

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Glossary

CDW: construction and demolition waste
CRA: coarse recycled aggregates
EU: European Union
FRA: fine recycled aggregates
IST: Instituto Superior Técnico, University of Lisbon, Portugal
LNEC: Portuguese National Laboratory of Civil Engineering, Lisbon
NA: natural aggregates
RA: recycled aggregates
RC: reference concrete (without recycled aggregates)