Long-term behaviour of concrete produced with recycled lightweight expanded clay aggregate concrete

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HIGHLIGHTS

- Concrete with recycled lightweight concrete aggregates (RLCA).
- Long-term term behaviour of recycled lightweight concrete (RLWC).
- Shrinkage, capillarity, immersion absorption, carbonation, chloride penetration.
- General reduction of the long-term properties with the incorporation of RLCA.
- RLWC may be a viable alternative solution with higher structural efficiency.

ARTICLE INFO

ABSTRACT

In this paper some of the main long-term properties of concrete produced with recycled aggregates obtained from crushing both structural and non-structural lightweight concrete (LWC) are analysed. The properties studied are drying shrinkage, capillary and immersion absorption, and carbonation and chloride penetration resistance. A comprehensive experimental study was carried out on a series of concrete mixes in which ratios of 20%, 50% and 100% of two types of coarse lightweight aggregates (LWA) were replaced with two types of recycled lightweight concrete aggregates (RLCA). Long-term shrinkage is affected by the paste adhered to LWA and increases as the replacement ratio of LWA with RLCA goes up. However, the internal curing promoted by RLCA reduces the early shrinkage. In terms of durability, the experimental results show that generally all the properties studied decay due to the progressive replacement of structural LWA with RLCA. However, despite the general reduction of long-term properties, recycled lightweight concrete (RLWC) can be also durable, regardless of the type of RLCA. Moreover, it is shown that even for low to moderate strength RLWC the mechanism of carbonation is not a determinant factor for durability. On the other hand, the carbonation and chloride penetration resistance of concrete with non-structural LWA tends to improve with the incorporation of RLCA. It can thus be concluded that RLWC may be a viable and more cost-effective alternative solution, especially given its higher structural efficiency. In addition, RLCA obtained from non-structural LWC can be incorporated in concrete without significantly compromising its durability.

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1. Introduction

Environmental sustainability has been one of the main issues troubling human society in recent decades. The construction sector is involved in an abusive use of natural resources and the production of large amounts of waste. Indeed, the concrete industry is still the largest user of natural resources in the world. It is estimated that it consumes about 1.2 billion tonnes of cement and 7.5 billion tonnes of aggregates annually [1]. In addition to this significant environmental impact, a growing amount of waste results from the demolition of concrete structures. Replacing natural aggregate

wholly or partially with recycled aggregate has been one of the options most often used to achieve a more sustainable construction [2].

Lightweight concrete (LWC) is an alternative solution to normal weight concrete (NWC), especially when lighter and more energy-efficient solutions are required [3–5]. Contrary to normal weight concrete, the density of lightweight concrete is usually below 2000 kg/m^3 and its thermal conductivity is as much as 1.0 W/m °C [3,6]. Owing to these features, since the middle of the 20th century LWC has been widely used in bridges and buildings, especially in non-structural applications [4,5].

Presently there is no accurate estimate of the total LWC waste produced every year, but its reuse and recycling is still not a common practice. Moreover, artificial LWA is very costly to produce in terms of energy consumption, which has serious economic and environmental impacts.

It is therefore useful to explore more cost-effective and environmentally-friendly solutions based on lightweight concrete produced from secondary lightweight sources. Not only will this reuse otherwise useless waste but it can also greatly reduce the extraction of natural resources and energy consumption.

Several recent studies have characterised the physical and mechanical properties and durability of recycled normal weight concrete (RNWC) (e.g. [2,7–10]).

Recycled concrete aggregate (RCA) differs from natural aggregates (NA) mostly because of the adhered mortar on its surfaces [2,10,11]. Therefore, RCAs usually have higher porosity, lower bulk density and lower crushing strength than NAs [7,12,13]. Because of these specific properties, it is reported that the density [10,12,14], compressive strength [15–18] and modulus of elasticity [10,16] of concrete usually decrease with increasing RCA content. Bazuco [12] reported a compressive strength reduction of 14–32% in RNWC. According to Tavakoli and Soroushian [19] the weaker aggregate/old paste transition zone in RCA lowers the strength of RNWC. The reduction in the modulus of elasticity is usually even greater because the concrete stiffness is more significantly affected by the aggregates' properties.

The lower stiffness of RCA is the main reason for the usually higher shrinkage of concrete produced with recycled normal weight aggregates [20–22]. Hansen and Boegh [22] found that shrinkage was 70% higher when natural aggregates were totally replaced by coarse and fine RCA. However, Evangelista and de Brito [10] found that the internal curing provided by RCA can beneficially delay drying shrinkage and also extend the hydration reactions of RNWC.

It should be noted that the physical, mechanical and durability properties of concrete produced with RCA can vary considerably according to the quality and content of the old mortar surrounding the primary aggregates.

Regarding durability, it is usually reported that normal weight concrete produced with RCA has a worse long-term performance than traditional NWC of equivalent composition [2,10,21]. Buttler [21] reported 40% greater water absorption by immersion in RNWC because of the higher porosity of recycled aggregates. Similar findings were obtained by Kwan et al. [2]. The higher porosity of RCAs is also responsible for the lower carbonation resistance of RNWC [20]. A reduction of 65% in carbonation resistance was obtained by Evangelista and de Brito [10] in concrete produced with fine RCA. A slightly smaller reduction of 30% compared to conventional concrete was reported by Amorim et al. [23] for concrete produced with coarse RCA.

On the other hand, Levy [24] found that the chloride penetration in RNWC was 36% higher than in conventional concrete, and concluded that the higher the replacement percentage of aggregates by RCA the lower the durability performance of RNWC. Similar conclusions were drawn by Evangelista and de Brito [10] for

recycled concrete produced with coarse and fine RCA and they also report a linear correlation between the chloride penetration of RNWC and its water absorption by immersion. However, several authors believe that the chloride penetration and the carbonation resistance should be affected more by the quality of the paste than by the type of aggregate [24–26].

To the best of our knowledge only a few studies have been published on the production and characterisation of recycled lightweight concrete (RLWC) and these basically only focus on their mechanical properties. EuroLightConR26 [27] presents a short study where the compressive strength of a recycled modified density concrete (2180 kg/m^3) produced from a mixture of brick and concrete aggregates is compared with the compressive strength of a conventional concrete. Kralj [28] analysed the compressive strength and thermal conductivity of non-structural lightweight concrete with recycled aggregates containing expanded glass.

Reinhardt and Kummel [29] studied the shrinkage of concrete produced with recycled expanded clay lightweight concrete aggregates. The authors found that shrinkage increased as the percentage replacement of natural aggregates with recycled lightweight concrete aggregates (RLCA) also increased. The shrinkage increment was nearly 50% for concrete with 54% RLCA.

In a more recent work, Figueiredo [30] studied the main physical and mechanical properties of RLWC produced with partial or total replacement of LWA with RLCA. The authors found that the compressive strength, tensile strength, modulus of elasticity and abrasion resistance generally improved with the incorporation of RLCA. In particular, concrete with RLCA showed higher structural efficiency than the reference concrete, with 100% LWA.

This paper aims at characterising the long-term behaviour of concrete produced with the partial or total replacement of LWA with recycled aggregates obtained from crushing both structural and non-structural lightweight aggregate concrete. The shrinkage, absorption, chloride penetration and carbonation resistance of RLWC are investigated and compared with those of conventional LWC using expanded lightweight aggregates.

2. Experimental programme

2.1. Materials and methods

The experimental work reported in this paper involved the characterisation of various concrete mixes produced when 20%, 50% and 100% of two types of coarse lightweight expanded clay aggregates (LWA) were replaced with crushed LWC aggregates obtained from concrete slabs previously produced with the same types of LWA. The two types of LWA were Leca M and Leca HD from Portugal. Their particle dry density, ρ_p, loose bulk density, ρ_b, crushing strength and 24 h water absorption, $w_{abs,24h}$, are listed in Table 1. A more detailed microstructural characterisation of these aggregates can be found elsewhere [30,31].

Given their specific properties, the selected LWA are classed as type LM (Leca M) and type LHD (Leca HD), which represent LWA of high and low porosity for non-structural and structural purposes, respectively. The two types of recycled lightweight concrete aggregates (RLCA), RM and RHD, were obtained, respectively, from a no-fines non-structural lightweight concrete produced with LM (LWCM) and a structural concrete produced with LHD (LWCHD) (Fig. 1). After 28 days the concrete slabs produced in the laboratory were crushed in a jaw crusher and the recycled aggregates were separated by size fraction. The composition of the original concrete is provided in Table 2 and the properties of the recycled aggregates RM and RHD are listed in Table 1. Fine aggregates consisted of 2/3 coarse and 1/3 fine normal weight sand. Their main properties are also presented in Table 1. Cement type I 42.5 R was used.

Contrary to recycled normal weight aggregates, the dry particle density of RLCA increased 60% (RM) and 50% (RHD) when compared to the original LM and LHD (Table 1). This is due to the higher density of the adhered mortar on the surface of RLCA. As also expected, the absorption is higher in RLCA than in the original LWA. This can be explained by the higher content of broken particles in RLCA and also by the adhered mortar surrounding the original LWA. It is thus clear that the RLCA characteristics and the concrete produced with them are strongly affected by the mortar adhered to the primary LWA. RHD contains about 36% LHD and 64% mortar and RM contains about 63% LM and 37% paste. This is easily determined from the density of LWA and RLCA (Table 1) and by knowing the density of the old mortar present in RLCA. Taking this into account, Table 2 shows the total

Table 1
Aggregate properties.

Property	Natural sand		Lightweight aggregates		Recycled LWA	
	Fine sand	Coarse sand	LHD 4–12	LM 4–12	RHD	RM
Particle dry density, ρ_p (kg/m³)	2604	2610	1092	595	1735	878
Loose bulk density, ρ_b (kg/m³)	1495	1493	681	339	1000	463
24 h water absorption, $w_{abs,24h}$ (%)	0.2	0.2	12.6	23.2	15.7	29.4
Crushing strength (MPa)	–	–	5.7	1.2	7.6	2
Sieve size fraction (d_i/D_i)	0/1	0/4	4/11.2	4/11.2	0.5/16	0.5/16
Shape index (EN 933-4)	–	–	–	–	23.9	8.8

Fig. 1. Original structural LWCHD (left) and no-fines non-structural LWCM (right).

percentage of mortar and original LWA for each concrete mix. It is shown that replacing LWA with RLCA leads to an overall reduction of the total volume of coarse aggregates in concrete and a consequent increment in the volume of mortar. The increment of mortar is higher in concrete with RHD because RM was obtained from concrete produced without fines (Fig. 1).

2.2. Mix proportions, concrete mixing and tests

Four concrete families comprising twelve mixes were produced with a replacement ratio of 0% (reference concrete-RC), 20%, 50% and 100%, as listed in Table 2. To ensure comparability, the mixes were produced with the same target slump of 125 ± 10 mm. The maximum aggregate size was 11.2 mm. All concrete compositions are given in Table 2. The water/cement ratio (w/c) indicates the effective water available for cement hydration. Different size fractions of RLCA were combined to give the same grading curve as the original LWA.

The mixes were produced in a vertical shaft mixer. The coarse aggregate and natural sand were wetted for 3 min with 50% of the total water before mixing. The absorption of LWA and RLCA in the mix was estimated beforehand to take into account the correction of the total mix water, according to Bogas et al. [32]. The cement and the rest of the water were then added. The total mixing time was 7 min.

The following specimens were produced for each mix: five 150 mm cubic specimens for compressive strength tests at 28 days according to EN 12390-3 [33]; eight sawed ∅100 × 40 mm cylindrical specimens for accelerated carbonation tests according to LNEC E391 [34]; six sawed ∅100 × 50 mm cylindrical specimens for rapid chloride migration tests according to NTbuild492 [35]; three sawed ∅150 × 50 mm cylindrical specimens for capillary absorption tests according to LNEC E393 [36] and TC116-PCD [37]; three 100 mm cubic specimens for water absorption tests by immersion according to LNEC E394 [38]. In addition, for each composition, two 150 × 150 × 600 mm prisms were produced to measure total drying shrinkage according to LNEC E398 [39].

2.2.1. Curing process

After demoulding at 24 h, the specimens were stored for curing. Four curing processes were adopted. For compressive strength, absorption by immersion and chloride penetration tests the specimens were kept in water until testing. For capillary absorption, the specimens were kept in water for 7 days and then oven dried for 3 days at 50 °C, followed by 17 days at 50 °C and 1 day at 20 °C without moisture exchange. This allows the redistribution of the water content across the specimen. For carbonation tests, the specimens were kept in water for 7 days and then stored at 22 ± 2 °C and relative humidity of 50 ± 5%. The specimens subjected to drying shrinkage were exposed to air at 22 ± 2 °C and 50 ± 5% relative humidity.

2.2.2. Absorption tests

The water absorption by immersion was measured after 28 days. The specimens were removed from the water and the saturated surface dry weight was recorded. The specimens were then oven dried at 105 °C until constant mass and the absorption was calculated based on the dry weight.

The capillary absorption test basically consists of determining the water absorption rate (sorptivity) by measuring the increase in the mass of a specimen due to absorption of water as a function of time, when only one surface of the specimen is exposed to water. The exposed surface of the specimen is immersed in 5 ± 1 mm of water and the absorption of unsaturated concrete is dominated by capillary suction. For each composition, three ∅150 mm × 50 mm tall cylindrical specimens were tested at 28 days. The mass of the specimens was recorded 15, 30, 60 min and 3, 6, 24 and 72 h after the initial contact with water, and the water absorption at each age was calculated. In addition, the absorption coefficient was taken to be equivalent to the slope of the linear regression line between √30 min and √24 h (linear region).

2.2.3. Carbonation resistance

After curing, the top and the bottom surfaces of the sawed specimens obtained from cylinders were painted so that only lateral diffusion of CO_2 was possible.

The specimens were then exposed in a controlled closed chamber at 23 ± 3 °C, 60 ± 5% relative humidity and 5 ± 0.1% of CO_2, to accelerate the effect of carbonation, according to LNEC E391 [34]. The specimens were subjected to accelerated carbonation for 120 days.

Carbonation depths were measured using a phenolphthalein indicator on the exposed surfaces of split cylindrical specimens. The average of seven measurements in each of the four broken parts was recorded as the carbonation depth. Two specimens were tested for each composition at a given age.

The depth of carbonation, x_c, over time can be approximately determined by expression Eq. (1), where K_c is the coefficient of carbonation obtained from the linear regression between x_c and t^n, and n is usually assumed to be 0.5, especially when the test conditions are maintained over time, as in the accelerated tests conducted in this study [40–43].

$$x_c = x_0 + K_c t^n \qquad (1)$$

2.2.4. Chloride penetration resistance

The chloride penetration resistance was assessed by means of the non-steady state rapid chloride migration test (RCMT) specified in NTDbuild492 [35], also called 'Nordtest'. In this test, an external electrical potential was applied axially across the specimens and forced the chloride ions outside to migrate into them. After a given period, the specimen was split axially and a silver nitrate solution was sprayed on one of the freshly split sections. The chloride penetration depth was then measured from the visible white silver chloride precipitation. Finally, the non-steady-state chloride migration coefficient (D_{nscm}) can be calculated according to Eq. (2), where: U is the absolute value of the applied voltage (V); T is the average value of the initial and final temperatures in the anolyte solution (°C); L is the thickness of the specimen (mm); x_d is the average value of the penetration depths (mm); t is the test duration (h).

$$D_{nscm} = \frac{0.0239 \cdot (273 + T) \cdot L}{(U - 2)t}\left(x_d - 0.0238\sqrt{\frac{(273 + T) \cdot L \cdot x_d}{U - 2}}\right)\left[\times 10^{-12} \text{ m}^2/\text{s}\right] \qquad (2)$$

Table 2
Mix proportions and concrete density.

Mixes	RALC (%)	Coarse LHD (L/m³)	Coarse LM (L/m³)	Coarse RHD (L/m³)	Coarse RM (L/m³)	Coarse sand (kg/m³)	Fine sand (kg/m³)	Cement (kg/m³)	Effect. water (L/m³)	Effect. w/c	Slump (mm)	Density Fresh, ρ_f (kg/m³)	Density Dry, ρ_d (kg/m³)	Mortar fraction (%)	Original LWA (%)
LWCHD	0	350	–	–	–	565	260	350	192.5	0.55	–	–	–	65.0	35.0
LWCM	0	–	630	–	–	–	–	150	90	0.60	–	–	–	–	63.0
CHD	0	350	–	–	–	565	260	350	192.5	0.55	130	1897	1628	65.0	35.0
CHD20RHD	20	280	–	70	–	565	260	350	192.5	0.55	120	1910	1672	69.5	30.5
CHD50RHD	50	175	–	175	–	565	260	350	192.5	0.55	130	1983	1739	76.2	23.8
C100RHD	100	0	–	350	–	565	260	350	192.5	0.55	125	2092	1852	87.4	12.6
CHD20RM	20	280	–	–	70	565	260	350	192.5	0.55	135	1888	1612	67.6	32.4
CHD50RM	50	175	–	–	175	565	260	350	192.5	0.55	125	1866	1590	71.5	28.5
CM	0	–	350	–	–	565	260	350	192.5	0.55	125	1710	1453	65.0	35.0
CM20RM	20	–	280	–	70	565	260	350	192.5	0.55	130	1761	1473	67.6	32.4
CM50RM	50	–	175	–	175	565	260	350	192.5	0.55	130	1809	1503	71.5	28.5
C100RM	100	–	0	–	350	565	260	350	192.5	0.55	125	1842	1552	78.0	22.1
CM20RHD	20	–	280	70	–	565	260	350	192.5	0.55	130	1728	1533	69.5	30.5
CM50RHD	50	–	175	175	–	565	260	350	192.5	0.55	125	1897	1653	76.2	23.8

2.2.5. Drying shrinkage

The total axial shrinkage was monitored by a demountable mechanical strain gauge (DEMEC) with a precision of 1 μm and a gauge length of 5 mm. The DEMEC was placed over two steel pins, 200 mm apart, which were glued to one of the concrete's moulded surfaces (Fig. 2). The drying shrinkage was measured from the demoulding age of 24 h up to 90 days.

3. Results and discussion

For better interpretation, the results are presented divided by series of RLWC: the series with LHD and its partial replacement with RHD (series CHDRHD) or RM (series CHDRM); the series with LM and its partial replacement with RHD (series CMRHD) or RM (series CMRHD). The average values of compressive strength, f_{cm}, structural efficiency, f_{cm}/ρ_d, carbonation depth (x_c), diffusion coefficient of non-steady-state chloride migration (D_{nscm}), absorption by immersion (abs_i), capillary absorption at 72 h ($c_{abs,72h}$), coefficient of capillary absorption (CA) and drying shrinkage at 90 days (ε_{cs}) are listed in Table 3. The coefficient of carbonation, K_c, which corresponds to the slope of the linear regression of the carbonation depth *versus* the square root of time, is also given in Table 3 (Section 2.2.3).

3.1. Compressive strength and structural efficiency

Generally the compressive strength increases as the LWA is replaced with greater amounts of the stronger RLCA (Table 3). The increment is up to 14% when LHD is totally replaced with RHD and 74% when LM is replaced with RM. This is explained by the higher crushing strength of RLCA and the reduction in the volume of coarse lightweight aggregate in the mix. A more detailed mechanical characterisation of these concretes is provided in [30].

As expected, the hardened concrete density increases proportionally to the replacement of LWA with the heavier RLCA (Table 3). However, the concrete dry density is less than 2000 kg/m³ for all mixes, in agreement to what is required in EN 206-1 [44] for LWC. Moreover, the slight increase in density of RLWC is usually offset by a greater increase in its compressive strength. In fact, it is found that the structural efficiency (f_{cm}/ρ_d) increases as LWA is progressively replaced with RLCA. This is a very interesting finding that makes recycled lightweight concrete a very competitive alternative to conventional LWC.

As discussed in [30], there is an important increment in the ceiling strength of RLWC with the incorporation of RLCA, not only because the strength capacity of RLCA is higher but also because there is a greater mobilisation of the mortar strength. Note that the 100% replacement of LWA with RLCA corresponds to an effective aggregate replacement of only 63% (RM) and 36% (RHD) (Table 3). The rest is additional mortar.

It is also interesting that the structural efficiency of LWC with LHD is only slightly lower when the weaker RM is incorporated. In other words, the recycled aggregates obtained from non-structural concrete can be used in structural LWC without greatly compromising its mechanical properties.

3.2. Drying shrinkage

As shown in Figs. 3–6, the drying shrinkage tends to increase with the incorporation of greater amounts of RLCA. These results agree with those of Reinhaud and Kummel [29] also for concrete produced with recycled expanded clay aggregates. In fact, as mentioned above, replacing LWA with RLCA leads to an increment of the volume of paste, which is the source of shrinkage, thus explaining the increment of the drying shrinkage. In other words, the higher amount of mortar in RLWC offsets the lower stiffness of LWA.
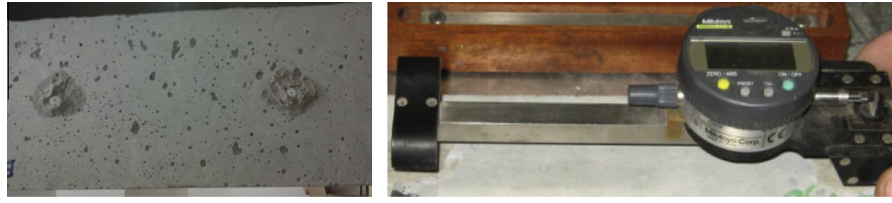
Fig. 2. Shrinkage measure: prisms of 150 × 150 × 600 mm (left); shrinkage monitoring (right).

Table 3
Compressive strength, drying shrinkage, absorption, carbonation and chloride diffusion.

| Mixes	RALC (%)	Compressive strength		f_{cm}/ρ_d	Shrinkage	Capillary absorption		Absorption by immersion (%)	Carbonation resistance		Chloride diffusion	
		$f_{cm,28d}$	CV_{fc}	($\times 10^2$ m)	($\times 10^{-6}$ m/m)	$c_{abs,72h}$	CA		$x_{c,120d}$	K_c	D_{nscm} (10^{-2} m^2/s)	
		(MPa)	(%)	28 days	$\varepsilon_{cs,90d}$	(10^{-3} g/mm^2)	(10^{-3} mm/min$^{0.5}$)		(mm)	(mm/day)$^{0.5}$	28 days	90 days
LWCHD	0	37.2	3.6	–	–	–	–	–	–	–	–	–
LWCM	0	0.6	7.4	–	–	–	–	–	–	–	–	–
CHD	0	38.4	4.5	23.6	646	2.04	0.190	12.7	12.0	1.149	13.87	10.36
CHD20RHD	20	40.4	2.8	24.2	806	2.96	0.416	13.0	13.4	1.227	15.13	13.09
CHD50RHD	50	43.1	1.7	24.8	1020	4.42	0.423	14.2	13.9	1.205	15.34	14.27
C100RHD	100	43.7	1.7	23.6	1230	4.44	0.492	16.3	14.9	1.263	16.67	16.19
CHD20RM	20	38.5	2.8	23.9	954	3.29	0.361	15.0	14.2	1.304	11.94	12.66
CHD50RM	50	36.3	2.8	22.8	1060	3.60	0.413	18.7	15.0	1.311	13.50	11.97
CM	0	19.2	10.3	13.2	948	3.50	0.372	20.3	28.1	2.431	18.12	17.18
CM20RM	20	25.1	5.7	17.0	1010	3.17	0.346	21.0	21.7	1.859	17.92	14.67
CM50RM	50	27.7	4.8	18.4	1080	3.75	0.422	22.5	18.1	1.560	16.48	12.37
C100RM	100	33.4	5.1	21.5	1470	4.20	0.465	25.1	16.0	1.384	15.82	13.30
CM20RHD	20	26.4	3.8	17.2	984	3.71	0.392	18.9	19.9	1.716	14.03	11.59
CM50RHD	50	30.7	5.1	18.6	1230	3.97	0.416	17.1	16.1	1.319	15.68	14.45
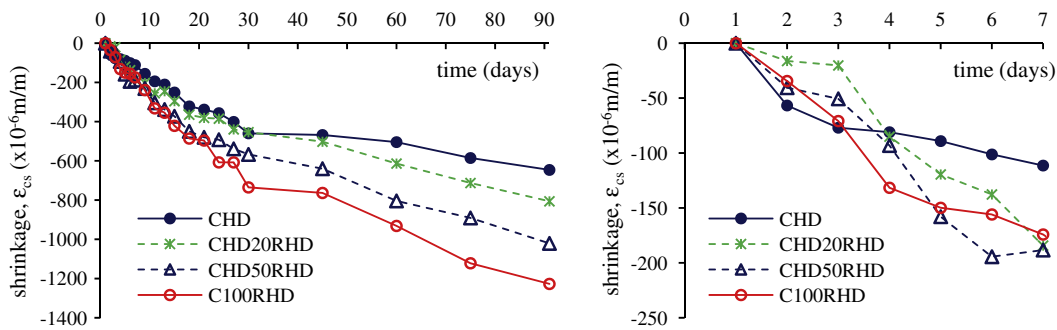
Fig. 3. Drying shrinkage up to 91 days (left) and up to 7 days (right) for series CHDRHD.
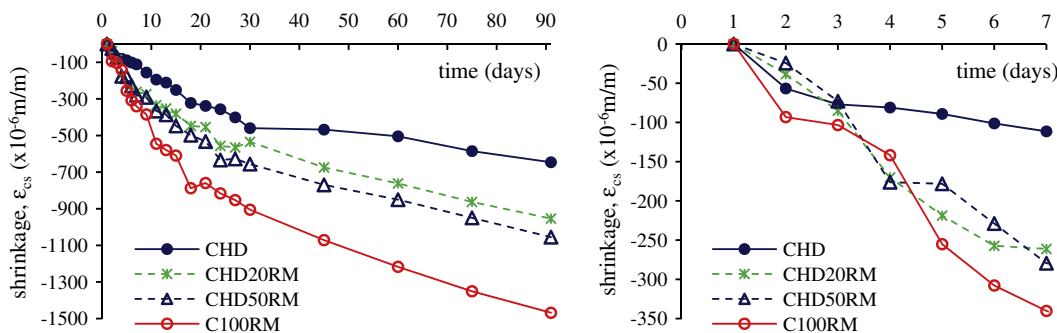

Fig. 4. Drying shrinkage up to 91 days (left) and up to 7 days (right) for series CHDRM.

At early ages, especially for series CHD, the shrinkage tends to be lower in concrete with RLCA (Figs. 3 and 4). At this stage, the water stored in recycled aggregates migrates to the paste and can compensate the evaporated water by internal curing. Similar conclusions were obtained by Zhang et al. [45] and Bogas et al. [46] for lightweight concrete. The old adhered mortar in aggregate increases its stiffness and restricts deformations.

For series CHDRHD, despite RLHD having higher strength than LHD, the amount of mortar added to the recycled aggregate causes an increase of the paste volume, which contributes to higher deformations.

The highest shrinkage increment is observed when LHD is replaced with RM (CHDRM) because RM has lower stiffness and higher amount of paste. In this case, the shrinkage is always higher
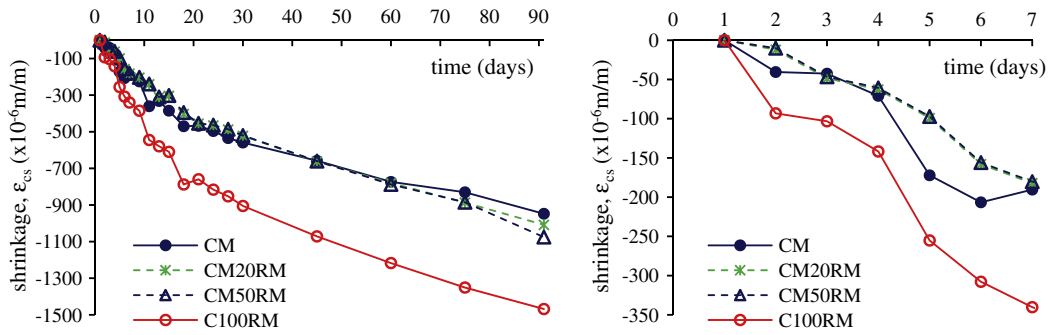
Fig. 5. Drying shrinkage up to 91 days (left) and up to 7 days (right) for series CMRM.
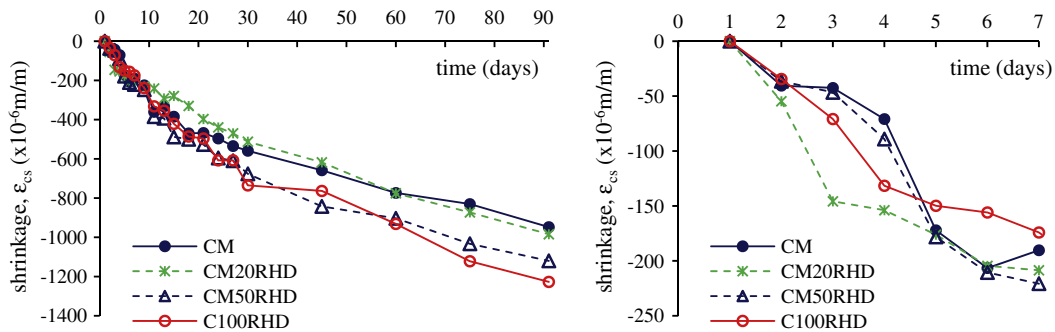

Fig. 6. Drying shrinkage up to 91 days (left) and up to 7 days (right) for series CMRHD.

in the recycled concrete, even at early ages, i.e. the higher absorption of RM does not compensate for its lower stiffness.

The shrinkage of series CMRHD is less affected by the replacement percentage of LM by RHD. Once more, despite the RHD having higher stiffness than LM, the more RHD incorporated the higher the final shrinkage. This is because the increment of the volume of paste outweighs the increment of the restriction effect provided by RHD. The more efficient internal curing provided by the more porous LM also probably contributes to the lower shrinkage, at least at early ages. But at later ages the lower restriction effect imposed by the weaker LM is more dominant. Except for C100RM, the shrinkage of series CMRM is little affected by the percentage replacement of LM with RM. Once more, the higher stiffness of RM seems to be offset by its higher amount of adhered paste.

In general, concrete with LM is less affected by the incorporation of RLCA than concrete with LHD, because RHD is much more rigid than LM and also the increment of adhered mortar in RM is less important. In addition, the incorporation of RM leads to slightly higher shrinkage than the incorporation of the same amount of RHD, because RM is much less rigid than RHD (Table 1).

Note, however, that the recycled aggregates used in this experiment were obtained from original concrete that was not allowed to dry until it was crushed to produce RLCA. The shrinkage of adhered paste would be less important for recycled aggregates obtained from old concrete and different conclusions may well be obtained.

3.3. Water absorption

The capillary water absorption after 72 h and the relevant coefficients of absorption are presented in Figs. 7 and 8, respectively. Fig. 9 shows the results obtained in the immersion tests.

3.3.1. Capillary absorption

Generally, the incorporation of RLCA in concrete increases the water absorption at 72 h, regardless of the type of the original and recycled aggregate. Similar trends are reported by other authors, but in concrete produced with recycled normal weight concrete aggregates [23,47]. For reasons that could not be identified, the results obtained for the control concrete CM are to some extent anomalous.

Lightweight concrete with the stronger LHD aggregate is more affected by the incorporation of RLCA than concrete with LM. Moreover, despite the higher absorption capacity of RM (Table 1), concrete with RHD has slightly higher absorptions than that with RM.

As RHD has a larger amount of adhered mortar than RM, this could be the main reason for the better behaviour of concrete made with the recycled non-structural RM aggregates. In fact, the finer porosity of the paste in the recycled aggregate is important to absorption as it can induce higher capillary forces.

Therefore, the adhered mortar seems to be more important than the overall porosity of aggregates, probably because of the low participation of the coarser pores of LWA in the capillary absorption. Since the porous structure of LWA is coarser than that of the paste,
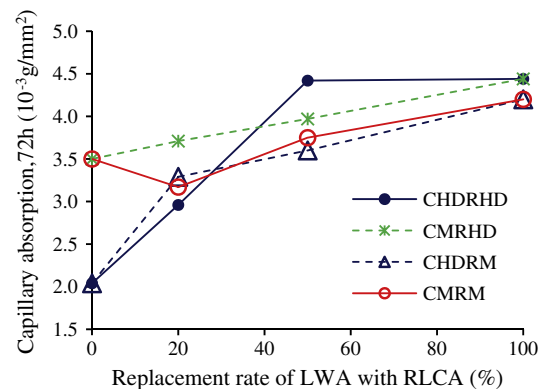

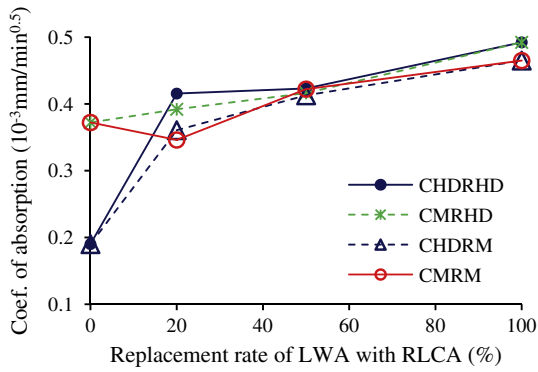**Fig. 7.** Influence of RLCA replacement on capillary absorption at 72 h.

Fig. 8. Influence of RLCA replacement on the coefficient of capillary absorption.
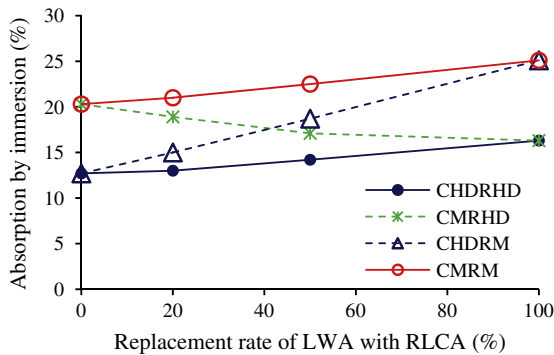

Fig. 9. Influence of RLCA replacement on the absorption by immersion.

there is a sharp decrease in the rate of absorption near the aggregates, i.e. the larger pores of LWA can cut the thinner capillary channels of the paste. This has also been shown by Bogas [48] in lightweight concrete and by Liou et al. [49] from analytical studies.

The higher amount of broken particles in recycled aggregates than in the primary LWA also contributes to higher absorption because the denser outer shell of the original LWA is partially lost. In this case, the integrity of the original LWA in no-fines non-structural LWC is less affected by the crushing process and the amount of broken particles in RM is lower than in RHD. As shown in Table 1, the nature of the original LWC makes the shape index of RHD much higher than that of RM. The less angular shape of RM results from the easier detachment of the agglutinated aggregates in no-fines low-strength concrete (Fig. 1). In addition, concrete with aggregate that is more porous often has higher water content, which also reduces capillary absorption. However, the increment of the volume of paste seems to be the most crucial factor.

Regarding the absorption coefficient, Fig. 8 shows that this also tends to increase with the replacement ratio of LWA by RLCA. Once more, this is explained by the increment of the volume of paste in concrete. The introduction of RHD leads to similar absorption coefficients in both families CHD and CM (Fig. 8). Moreover, slightly higher coefficients are observed with the incorporation of RM, which confirms that this property is related more to the increment of the volume of adhered paste in RLCA than to the porosity of the aggregates.

Table 3 shows that capillary absorption is not correlated with the compressive strength. Indeed, contrary to compressive strength, capillary absorption is affected far more by the volume of paste than by the aggregate's properties.

3.3.2. Water absorption by immersion

As expected, except for series CMRHD, water absorption by immersion increases along with the replacement ratio of LWA by

RLCA (Fig. 9). In this case, the water absorption, which is a measure of the total open porosity of concrete, correlates well with the absorption properties of the aggregates. Therefore, the incorporation of aggregates that are more porous, such as LM or RM (Table 1), leads to higher concrete water absorption. Fig. 9 shows that series CHDRM is affected most by the incorporation of recycled aggregate. For 100% replacement of LHD by RM there is an absorption increment of nearly 95% relative to the control concrete with LHD only (CHD). This is easily explained by the greater difference between the porosity of LHD and RM than in the other cases (Table 1). For the same reason, the total water absorption by concrete produced with LM falls if the less porous RHD is incorporated.

Absorption by immersion is not correlated with the compressive strength either, because higher strength recycled aggregates are not always associated with lower absorption properties (Table 1).

3.4. Carbonation resistance

As mentioned, the carbonation depth is roughly related to the root of time (Section 2.2.3), which is why the carbonation depth in Figs. 10–13 is shown as a function of $\sqrt{t}$. All the linear correlation coefficients are higher than 0.97, which means that Eq. (1) is adequate and the coefficient of carbonation, K_c, can be determined directly.

In general, as with absorption by immersion, carbonation depth tends to increase with the replacement ratio of LWA by RHD (Figs. 10 and 13). This was expected, since both properties strongly depend on the open porosity of concrete. In fact, the incorporation of aggregates that are more porous can contribute to a higher diffusion of CO_2 through concrete and hence a greater carbonation depth. Therefore, in series CHD the incorporation of RLCA in concrete with less porous LWA leads to an increase of the carbonation depth. The carbonation depth increment is greater when the more porous RM is incorporated, by up to 34% when compared to the reference concrete with LHD only (CHD). Also as expected, the incorporation of RHD in series CMRHD with the more porous LM leads to a decrease of the carbonation depth.

The behaviour of series CMRM was less expected. Despite RM having higher porosity than LM, the carbonation depth decreases with the incorporation of RM. However, the adhered paste may contribute to an improved binding of CO_2 and a better protection of the aggregate.

These factors also explain why the carbonation coefficients are not much affected when LHD is replaced by RM (Table 3, Fig. 14). In fact, for replacement ratios of LWA with RCA above 50%, the carbonation resistance is of the same order of magnitude, regardless of the type of original LWA.

According to the K_c values presented in Table 3 and Fig. 14, the rate of carbonation in conventional lightweight concrete with LM
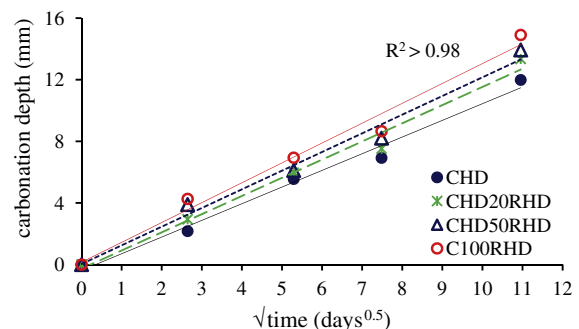

Fig. 10. Accelerated carbonation depth *versus* the square root of time up to 120 days – series CHDRHD.
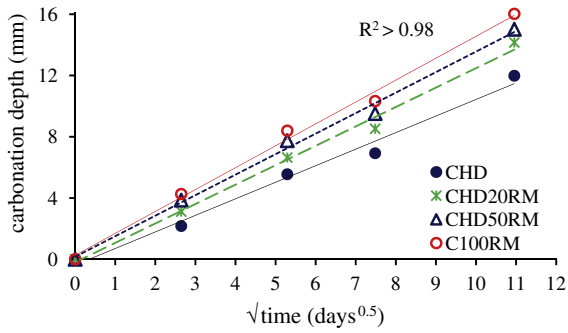
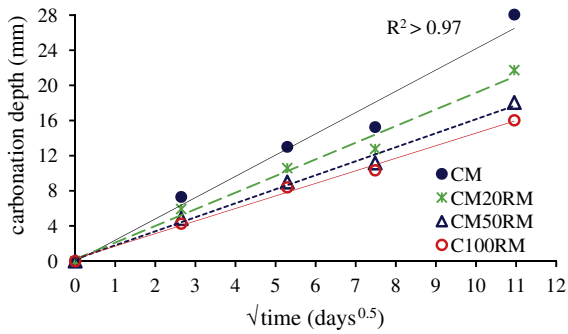**Fig. 11.** Accelerated carbonation depth *versus* the square root of time up to 120 days – series CHDRM.

Fig. 12. Accelerated carbonation depth *versus* the square root of time up to 120 days – series CMRM.
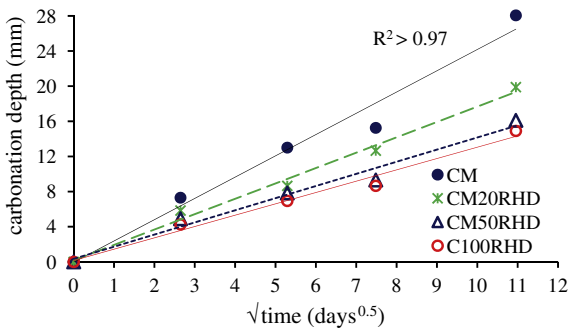

Fig. 13. Accelerated carbonation depth *versus* the square root of time up to 120 days – series CMRHD.

is about twice that of concrete with LHD. However, when recycled aggregates are incorporated the difference between mixes decreases, because the highly porous LM looses relevance. In fact, Table 3 and Fig. 14 show that the CM series are affected the most by the incorporation of RLCA. On the other hand, the carbonation coefficients are more similar in series CHD for different replacement ratios of LWA by RLCA, especially in series CHDRHD (Fig. 14). Two reasons for this are that the porosity of LHD and recycled aggregates is more similar, and that the same paste composition was adopted for RLCA and the concrete matrix.

In general, there is a poor correlation between the compressive strength and K_c (Table 3), because the strength of RLCA is not always correlated with its porosity (e.g. LHD *versus* RHD, see Table 1).

Using the carbonation coefficients listed in Table 3, we can roughly estimate the carbonation rate under real exposure conditions. For this, let us simply assume that the carbonation coefficients obtained from laboratory tests, $K_{c,lab}$, are related to those
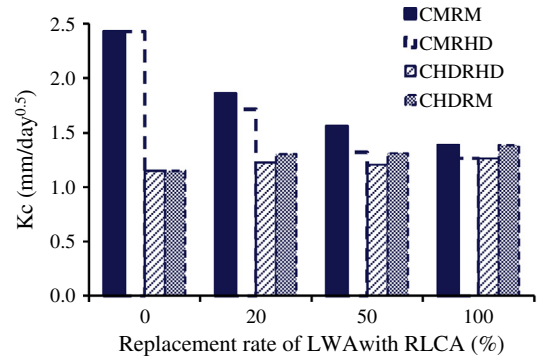

Fig. 14. Influence of RLCA replacement on the coefficient of carbonation, K_c.

obtained from real exposure conditions, $K_{c,real}$, according to Eq. (3), where $c_{c,real}$ is the concentration of CO_2 in real environment (0.7×10^{-3} kg/m^3 is assumed) and $c_{c,lab}$ is the concentration of CO_2 in the accelerated chamber (90×10^{-3} kg/m^3). The binding capacity and diffusion of CO_2 are simply assumed to be similar in the real and accelerated environment, which is not necessarily true.

$$K_{c,real} = K_{ca} \times \sqrt{\frac{c_{c,real}}{c_{c,acel}}} \qquad (3)$$

From Eq. (1) and Table 3, $K_{c,real}$ may generally vary between about 0.1 and 0.16 mm/day$^{0.5}$, depending on the type of original LWA and the type and incorporation percentage of RLCA. Based on Eq. (1), these coefficients correspond to a carbonation depth of only 25 mm after about 67–170 years, on average. Therefore, despite the high difference between mixes, it may be concluded that recycled lightweight concrete can also be an alternative durable solution. Also, the accelerated tests were performed under extremely severe and conservative environmental conditions, with a constant relative humidity of 65%.

It is interesting to compare the behaviour of the concrete produced with the non-structural aggregate LM only and that of the one with 20% RLCA. Depending on the type of RLCA, there is a 70% (RM) to 100% (RHD) increment in the predicted service life when 20% of LM is replaced with RLCA. In this case, the incorporation of RLCA proved to be very effective in improving carbonation resistance. Furthermore, the predicted service life in series CHD may vary as much as 45% when LHD is replaced by RLCA.

Our results can be compared with those obtained by Ho and Lewis [43] in normal weight concrete subjected to 4% CO_2 and 50% HR. Considering the conversion to 5% CO_2 based on Eq. (3), average values of about 1.5 mm/day$^{0.5}$ are estimated for a w/c ratio of 0.55, which are of the same order of magnitude as those obtained in our study.

3.5. Chloride penetration resistance

Except for series CMRM, the chloride diffusion coefficient generally tends to increase for higher percentage replacements of LWA by RLCA. However, coefficients of diffusion were not much affected by the incorporation of RLCA, especially in series CHD. Comparison of the results indicated that the chloride coefficient of diffusion at 28 days may vary as much as 20%, when LWA is replaced with RLCA.

In conventional concrete, this property is mostly related to mortar quality, since the aggregates do not allow the diffusion of chlorides. However, provided that concrete is tested under saturated conditions, as in our study, the diffusion through porous aggregates cannot be ignored, especially when the quality of the
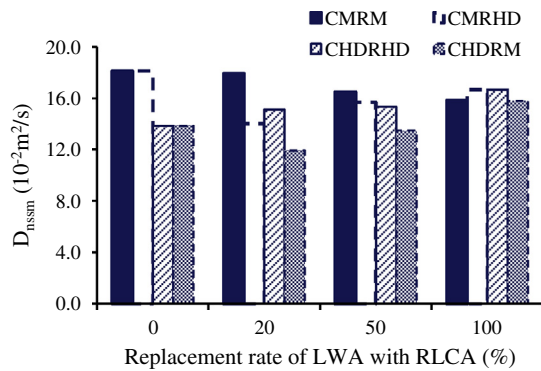
Fig. 15. Influence of RLCA replacement on the coefficient of chloride diffusion, D_{nscm}.

surrounding paste is low, such as in concrete with w/c ratio greater than about 0.45, and when the porosity of the aggregate is high [50]. The influence of the aggregate characteristics seems to be less important in high quality pastes with low interconnectivity, where the isolated porous aggregates are well protected by the paste [3,25,26,51].

Therefore, the higher porosity of RLCA may have an active role in chloride diffusion and reduce the chloride penetration resistance of concrete. This trend is shown in Fig. 15 for series CHD. However, small differences between results are in the range of the variability of the test, which complicates their accurate interpretation.

From the results obtained for series CHD it seems that the introduction of RM leads to lower diffusion coefficients than the incorporation of RHD. Moreover, the progressive incorporation of the less porous RHD in series CM leads to an unexpected increment of the chloride diffusion coefficient for replacement ratios above 20%. The higher amounts of both mortar and broken particles in RHD can partly explain the results (fewer barriers to chloride diffusion). The presence of two transition zones in RHD may also help explain the enhanced diffusion properties of recycled concrete. However, the same trend is not observed in series CM, for replacement ratios up to 50%. The results obtained are therefore not conclusive.

In addition, as observed for carbonation resistance, despite the higher porosity of RM relative to LM, the diffusion coefficient decreases as the incorporation of recycled aggregates increases (Fig. 15), and similar reasons can be singled out: the lower content and the protection effect of the adhered paste, and the higher amount of unbroken particles in RM than in RHD. This is also in line with the only slight variation of the diffusion coefficient when LHD is replaced with RM. As found in the absorption tests (Section 3.3), a less expected result was again obtained for the reference concrete with LM (CM).

Based on the same rapid chloride migration test, the document fib 34 [52] reports an indicative average diffusion coefficient of about 19.7×10^{-12} m/s for normal weight concrete with w/c ratio of 0.55, which is higher than our results. As expected, the diffusion coefficients obtained at 91 days were lower than the ones obtained at 28 days, because of the higher hydration degree/maturity of the paste. For reasons similar to those advanced for carbonation resistance (Section 3.4), there is a weak correlation between the compressive strength and the coefficient of chloride diffusion (Table 3).

4. Conclusions

This study analysed the long-term behaviour of recycled lightweight concrete produced by crushing both structural and non-structural lightweight concrete. The following main conclusions have been drawn:

- It is possible to make structural RLWC with crushed structural and non-structural lightweight concrete with density below 2000 kg/m³ and strength class ranging from LC20/22 to LC40/44. Contrary to non-structural LWA, the recycled aggregates from non-structural LWC are adequate for the production of structural lightweight concrete.
- The compressive strength and, most of all, the structural efficiency generally improves with the replacement of LWA with RLCA. The only exception is when structural LWA is replaced with recycled aggregates from crushed non-structural LWC, but even then both properties are only slightly reduced.
- Shrinkage is strongly affected by the paste adhered to the primary LWA and so this increases when LWA is replaced with RCA. This may not be valid for old RLCA with adhered mature pastes. However, the higher internal curing promoted by RLCA contributes to the shrinkage delay at early ages.
- Capillary water absorption increases for higher replacement ratios of LWA with RLCA, because this property is affected more by the adhered paste on RLCA than by the type of aggregate. On the other hand, water absorption by immersion is related more to the open porosity of concrete and so higher values are obtained in concrete produced with aggregates that are more porous.
- Except in concrete produced with non-structural LWA (LM) the carbonation resistance is only slightly increased with the incorporation of the more porous RLCA, regardless of the type of recycled aggregate. Concrete produced with LM benefits from the progressive incorporation of RLCA with an increment of efficient carbonation resistance of up to 70%.
- It can be concluded from this study that even with pastes of low to moderate quality the carbonation resistance of recycled lightweight concrete can be high enough, and the mechanism of carbonation is not crucial to durability. The total replacement of LWA by RLCA may, however, reduce the predicted service life of lightweight concrete by as much as 45–100%, depending on the type of original and recycled aggregate.
- The chloride diffusion coefficient in saturated specimens generally increases with the incorporation of RLCA. Besides the quality of the paste, the porosity of the aggregates, the amount of adhered mortar on RLCA and the percentage of broken particles are the main factors that affect the chloride penetration resistance of concrete. Our study found that the coefficient of diffusion varied as much as 20% when LWA was replaced with RLCA.

Overall, it can be concluded from this study that despite the general reduction of the long-term properties when LWA is replaced by RLCA, recycled lightweight aggregate concrete may be a viable alternative solution for the production of more sustainable structural lightweight concrete, especially given the improvement in its structural efficiency.

It can also be concluded that the recycled aggregates obtained from non-structural LWC are suitable for the production of cheaper structural lightweight concrete and do not significantly compromise its durability properties.

Acknowledgements

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