TÉCNICO LISBOA

Multiple recycling of concrete

Performance in terms of durability of concrete produced with coarse recycled aggregates obtained from multiple recycling

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Extended Abstract

Master's Degree in Civil Engineering

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1. Introduction

1.1. Preliminary remarks

Construction is one of the most waste generating activities in existence. It is estimated that during the year of 2014 the 28 countries belonging to the European Union generated about 821 million tonnes of waste related to Construction (Eurostat, 2016). Thus, multiple recycling of concrete presents itself as a possible alternative for the reutilization of construction and demolition waste.

Since there is not much scientific knowledge about the viability of the use of recycled aggregates obtained from multiple recycling on the production of concrete, as the very scarce literature available regarding this topic demonstrates, this dissertation intends to make a contribution to the scientific community in this regard.

Hence, this study presents the results and conclusions obtained from an extensive experimental campaign intended to study the durability performance of concrete produced with aggregates obtained from up to three recycling cycles.

1.2. Methodology

This investigation intends to study the influence of the use of aggregates obtained by the multiple recycling of concrete in terms of concrete durability properties. For this purpose, the experimental campaign was organised in three phases.

The first phase consists in the procurement of all the recycled coarse aggregates necessary for the study. Three different families were used, obtained from one (RCAI), two (RCAII) and three (RCAIII) recycling cycles. For this purpose, three mixes of source concrete were produced (OCI, OCII, OCIII) and later crushed with the help of a jaw crusher. The first source concrete (SCI) was made only with natural aggregates. Both the OCII and OCIII were produced with a 100% substitution of natural coarse aggregates with recycled coarse aggregates obtained from one and two cycles of recycling respectively.

In the second phase, seven more mixes were produced: a reference concrete, three mixes with 25% and three more with 100% substitution of NCA with RCA. Just like the SCI, the reference concrete (RC) was produced exclusively with natural aggregates. On the other hand, to produce the mixes with 25% and 100% substitution of NCA recycled coarse aggregate from one (C125%, C1100%), two (C225%, C2100%) and three (C325%, C3100%) recycling cycles were used. Figure 1 presents a schematic diagram of the methodology explained.

Finally, the third phase consisted in testing in terms of durability the seven concrete mixes referred above.

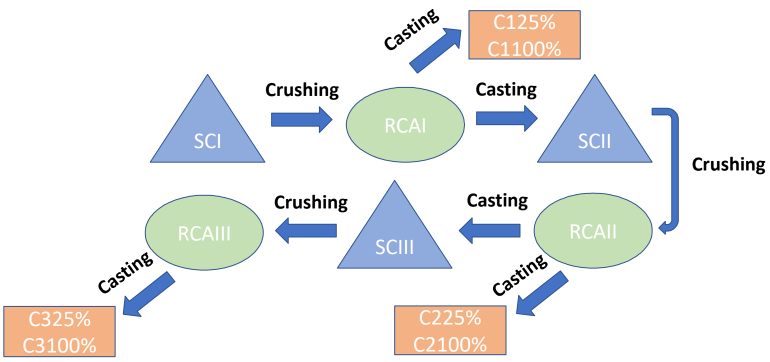


Figure 1 - Schematic diagram of the methodology used to produce all concrete mixes

2. Experimental campaign

2.1. Materials

Both natural and coarse recycled aggregates were used in the production of the concrete mixes.

Two different types of natural aggregates were used, silica sand and limestone. The recycled coarse aggregates were obtained from the multiple recycling of concrete with a design strength of 30 MPa. Overall, three cycles of recycling were made. Type I cement of class 42.5R and tap water were also used in the production of all mixes.

2.2. Concrete´s composition

To enable establishing a good comparison between all concrete mixes, a slump interval of 125 ± 15 mm for all mixes was fixed.

Because of the higher water absorption shown by the recycled aggregates, and taking in consideration Ferreira et al.'s (2011) conclusions about the disadvantages of the pre-saturation method, an adaptation of the method suggested by Rodrigues et al. (2013) was used in this study.

The preferred method allows determining the water absorption of the recycled aggregates at a given time, making it possible to adjust the w/c ratios during the mixing procedure of the concrete.

This implies that two different w/c need to be defined. The effective w/c is the ratio between water and cement without contemplating the additional water necessary to compensate the recycled aggregate absorption. On the other hand, the apparent w/c is defined as the ratio between the water and cement contemplating the water necessary to compensate the recycled coarse aggregate absorption.

All the mixes were designed in accordance with the Faury's method, taking in consideration the following assumptions: cement content of 350 kg/m^3; maximum particle size of 22.4 mm; design strength class of C30/37. Table 1 presents all the proportions of the components of the concrete mixes tested.

Table 1 - Composition of the concrete mixes [kg/m^3]

Components	# [mm]	RC	C125%	SCI & C1100%	C225%	SCII & C2100%	C325%	SCIII & C3100%
Natural coarse aggregate	4-5.6	97.2	72.9	-	72.9	-	72.9	-
	5.6-8	107.4	80.6	-	80.6	-	80.6	-
	8-11.2	116.0	87.0	-	87.0	-	87.0	-
	11.2-16	327.4	245.6	-	245.6	-	245.6	-
	16-22.4	327.4	245.6	-	245.6	-	245.6	-
Recycled coarse aggregate	4-5.6	-	86.8	21.7	81.3	20.3	79.4	72.9
	5.6-8	-	95.9	24.0	89.9	22.4	87.8	80.6
	8-11.2	-	103.4	25.9	97.0	24.2	94.8	87.0
	11.2-16	-	293.3	73.0	274.0	68.4	267.7	245.6
	16-22.4	-	292.2	73.0	274.0	68.4	267.7	245.6
Fine sand		250.7	250.7	250.7	250.7	250.7	250.7	250.7
Coarse sand		472.4	472.4	472.4	472.4	472.4	472.4	472.4
Cement		350	350	350	350	350	350	350
Water		193.6	193.6	193.6	193.6	193.6	193.6	193.6
Compensation water		-	40.33	10.11	48.56	12.11	54.89	13.67
$w/c_{effective}$		0.55	0.55	0.55	0.55	0.55	0.55	0.55
$w/c_{apparent}$		0.55	0.58	0.67	0.59	0.69	0.59	0.71

2.3. Aggregates testing

To determine the aggregates properties, several tests were performed. The size grading analysis followed the NP EN 933-1 (2000) and NP EN 932-2 (1999) procedures. The density and water absorption were determined according to NP EN 1097-6 (2003). The NP EN 1097-3 (2002) procedure was used to determine the bulk density. The Los Angeles abrasion test was performed according to NP EN 1097-2 (2011) and the shape index was determined according to the NP EN 933-4 (2002) standard. Finally, all the samples tested were prepared according to the percentage of each aggregate's size in concrete.

2.4. Concrete testing

All mixes were tested in the fresh state for workability and density according to the NP EN 12350-2 (2009) and NP EN 12350-6 (2011) standards respectively.

In the hardened state, concrete mixes were subjected to a variety of tests to determine their durability properties, as shown in Table 2.

Table 2 - List of tests performed concerning the hardened concrete mixes and standards used

Test	Standard	Age [days]
Compressive strength	NP EN 12390-3 (2011)	7, 28, 56
Shrinkage	LNEC E 398 (1993)	0-91
Water absorption by immersion	LNEC E 394 (1993)	28
Water absorption by capillary	LNEC E 393 (1993)	28
Carbonation resistance	LNEC E 391 (1993)	7, 28, 56, 90
Chloride penetration resistance	LNEC E 463 (2004)	29, 90

3. Experimental results and discussion

3.1. Aggregate properties

Since aggregates are a major constituent of concrete, they have a big influence on the quality of the mixes produced. Thus, the determination of their properties is fundamental to understand and correctly evaluate the performance of the concrete produced. Table 3 presents all the results obtained from the tests performed.

Table 3 - Aggregates tests results

Properties	NCA	RCAI	RCAII	RCAIII
Apparent density [kg/m^3]	2668.40	2668.06	2629.87	2672.23
Oven dried density [kg/m^3]	2593.04	2319.28	2175.01	2124.80
Saturated surface dry density [kg/m^3]	2621.28	2450.00	2347.97	2329.65
Bulk density [kg/m^3]	1355.1	1132.1	1034.4	990.1
Water absorption (24h) [%]	1.09	5.64	7.95	9.64
LA abrasion [%]	27.93	38.81	41.18	40.89
Shape index [%]	18	18	19	18

According to the results achieved, it can be said that the quality of the RCA is lower than that of the NCA. Additionally, it is also noted that in general the properties of the aggregate decrease as the number of recycling cycles increases. These results can be explained by the bigger porosity of the adhered mortar that is part of the RCA composition. In fact, with the increase of the recycling cycles, the quantity of adhered mortar also increases, consequently reducing the quality of the recycled aggregates.

However, as shown by the results, most of the properties studied present an asymptotic behaviour with the increase of the recycling cycle. This may indicate that the quantity of adhered mortar that takes part of the recycled aggregate composition tends to stabilize at the end of a given number of cycles. This behaviour is verified by the excellent correlations obtained with the exponential asymptotic model for the oven dried density (Figure 2), saturated surface dry density (Figure 3), bulk density (Figure 4) and LA abrasion (Figure 5).

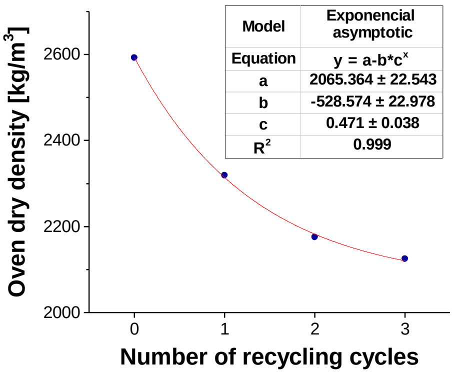


Figure 2 - Oven dry density as a function of the number of recycling cycles of the RCA

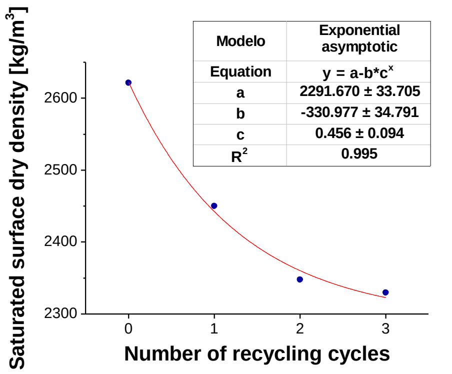


Figure 3 - Saturated surface dry density as a function of the number of recycling cycles of the RCA

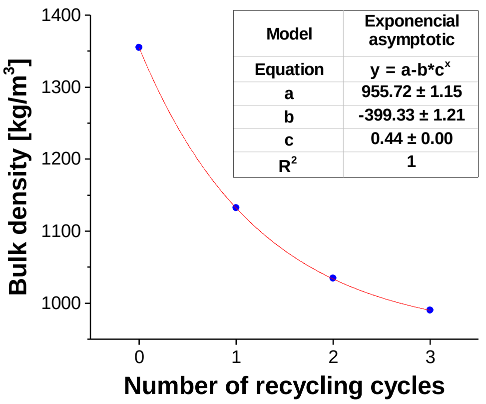


Figure 4 - Bulk density as a function of the number of recycling cycles of the RCA

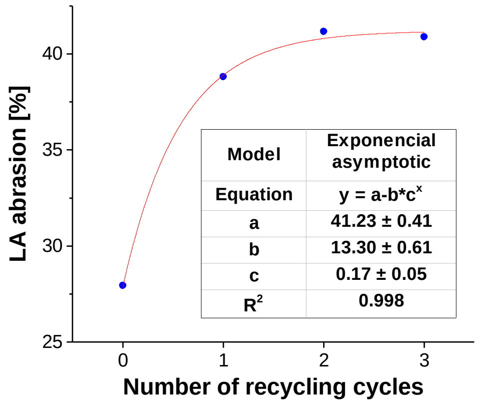


Figure 5 - LA abrasion as a function of the number of recycling cycles of the RCA

3.2. Fresh concrete properties

The concrete workability and density were tested in the fresh state. As stated in section 2.2, all mixes presented approximately the same workability, within the 125 ± 15 mm slump interval. However, contrary to what was observed by Huda and Alam (2014), no relevant loss of workability of the mixes that included aggregates from higher recycling cycles was noted. A possible explanation is the very similar shape index presented by the NCA and RCA (Table 3).

The results obtained for fresh density are presented in Table 4. It was observed that it followed the same asymptotic behaviour shown by the density of the recycled coarse aggregates (Figure 6). In fact, an excellent linear correlation can be established between the two parameters (Figure 7). Also, as can be seen in by the results obtained, the higher the percentage of substitution of NCA the lower the density values presented by the fresh concrete.

Table 4 - Average value of the fresh concrete density of all mixes

Fresh concrete density[kg/m³]	RC	C1100%	C125%	C2100%	C225%	C3100%	C325%
Average	2413.80	2319.30	2385.30	2279.80	2383.80	2264.80	2375.80

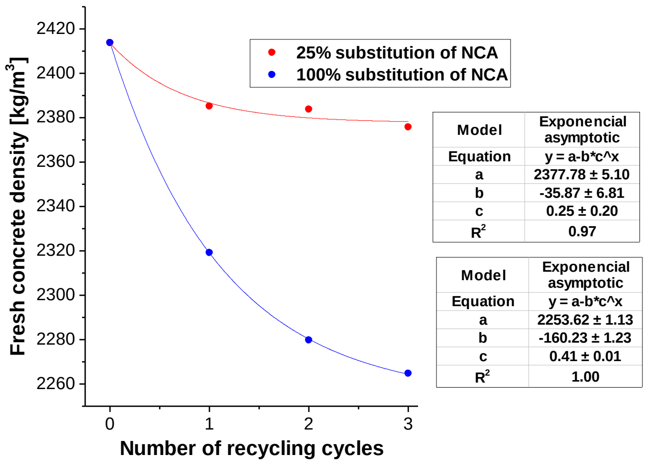


Figure 6 - Concrete fresh density as a function of the RCA number of recycling cycles of the RCA

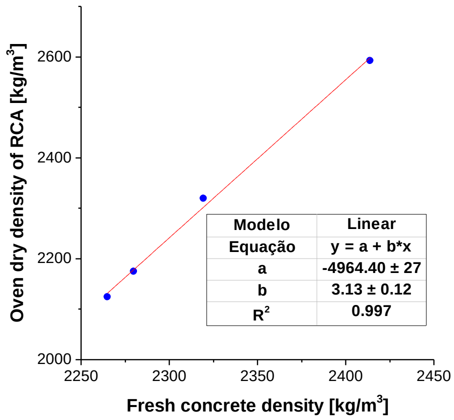


Figure 7 - Correlation between RCA oven dry density and the fresh density of concrete mixes with 100% substitution of NCA

3.3. Hardened concrete properties

3.3.1. Compressive strength

Even though this study focuses on the durability properties of the concrete, it is fundamental to evaluate the compressive strength resistance to have an idea of the quality of the concrete. The results obtained are presented in Table 5.

The results show that in all ages, the mixes with 100% of RCA showed a lower compressive strength than the RC. Also, the higher the recycling cycles of the RCA the lower the performance presented by the mixes. On the other hand, mixes with 25% substitution of NCA did not demonstrate such an evident trend. In fact, only the compressive strength of the C325% mix was always lower than the RC. This may suggest that this property is not significantly influenced by low percentages of incorporation of RCA.

Table 5 - Compressive strength results at 7, 28 and 56 days

Compressive strength [MPa]			
Concrete	**7 days**	**28 days**	**56 days**
RC	46.2	55.9	63.8
C125%	47.6	59.7	65.0
C225%	47.0	55.9	60.7
C325%	45.2	55.9	62.7
C1100%	44.0	54.1	59.0
C2100%	43.3	53.3	57.6
C3100%	40.3	48.6	56.2

3.3.2. Shrinkage

Figure 8 shows the results obtained for shrinkage deformation. As expected, mixes with higher percentage of substitution of NCA present a higher shrinkage deformation. This can be explained by the lower stiffness of the recycled aggregates. In fact, the bigger the quantity of adhered mortar that constitutes the aggregate the less stiffness it has, hence the lower resistance it shows to deformation. This explains the worse results obtained by mixes with recycled aggregates obtained from a higher number of recycling cycle.

As seen in Figure 8, the evolution of shrinkage deformation in all mixes presents a non-linear behaviour. It is much more relevant in the first ages than in the older ones, as expected. Additionally, until 7 days of age the concrete mixes with incorporation of RCA show very similar results to the ones presented by the

RC. This can be due to the higher porosity of the recycled aggregates, which allows them to retain water. This water is then gradually released allowing for an internal curing, which slows down the shrinkage deformation in the first ages of concrete. It can also be stated that the 91 days of duration of the test were not enough to verify a stabilization of the deformation by shrinkage on all the mixes in study.

Furthermore, although good correlations factors have been obtained with the use of the exponential asymptotic model, three recycling cycles are not enough to verify a stabilization of this property (Figure 9). This is corroborated by the unacceptable large error intervals of the asymptotes obtained.

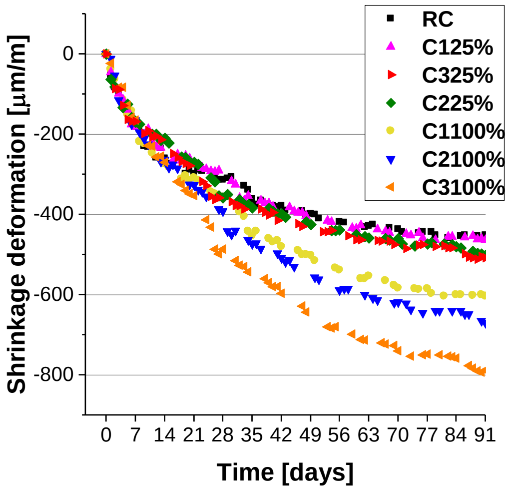


Figure 8 - Evolution of shrinkage deformation over time

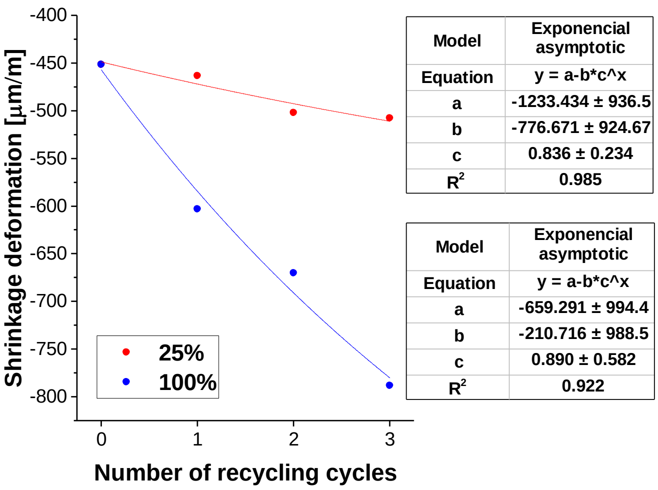


Figure 9 - Shrinkage deformation at 91 days for mixes with 25% and 100% substitution of NCA as a function of the number of recycling cycles of the RCA

3.3.3. Water absorption by capillary and immersion

Table 6 presents the obtained results of water absorption by capillary and immersion, as well as the comparison of every concrete mix with the RC at the end of the test (% $_{RC}$).

The results show that every mix that incorporates recycled aggregates present a bigger water absorption than the RC. Also, as seen in other properties, the bigger the number of the recycling cycle of the aggregates utilized, the worse the quality of the concrete is. This is again due to the higher porosity presented by the adhered mortar and by its bigger presence in the constitution of aggregates that are obtained from higher number of recycling cycles. Furthermore, both these properties are also affected by the amount of water used in the mixing procedure of concrete, which increases as the amount of recycling cycles needed to obtain the RCA also increases (Table 1).

Table 6 - Water absorption by capillary results and comparison with the RC

Concrete	Water absorption by capillary (72 h) [x10^{-3} g/mm^2]	% $_{RC}$	Water absorption by immersion [%]	% $_{RC}$
RC	3.43E-03	-	13.45	-
C125%	5.84E-03	70.26	15.26	13.46
C225%	6.25E-03	82.22	15.69	16.65
C325%	6.57E-03	91.55	16.06	19.41
C1100%	7.53E-03	119.53	18.60	38.29
C2100%	9.21E-03	168.51	21.67	61.12
C3100%	10.70E-03	211.95	21.72	61.49

As seen in Figure 10, the water absorption by capillary of the mixes with 25% and 100% substitution of NCA present an asymptotic behaviour in regard to the number of recycling cycles. This is also the case for the water absorption by immersion (Figure 11).

Furthermore, since the result obtained for the water absorption by immersion for the C325% (16.06%) and C3100% (21.72%) mixes are within the error range of the asymptotes given by the exponential asymptotic model (16.095±0.18% for 25% and 22.637±1.19% for the 100%), it can be concluded that three recycling cycles were enough to achieve stabilization of this property.

This is also true for water absorption for capillary for the mixes with 25% substitution of NCA, since the result obtained for C325% (6.57×10^{-3}) also is inside the error range of asymptote given by the correlation model ($6{,}536\times10^{-3}\pm0{,}146\times10^{-3}$).

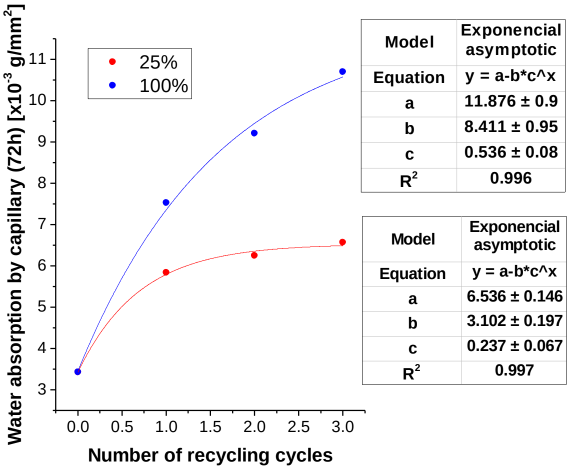


Figure 10 - Capillary absorption of mixes with 25% and 100% substitution of NCA as a function of the number of the recycling cycles of the RCA

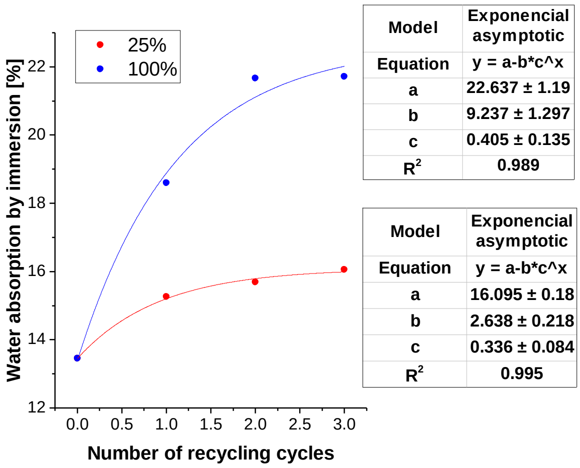


Figure 11 - Water absorption by immersion of mixes with 25% and 100% substitution of NCA as a function of the number of the recycling cycles of the RCA

3.3.4. Carbonation

The carbonation resistance essentially depends on the diffusion capacity of concrete. Since recycled aggregates have a bigger porosity, it is expected that mixes with bigger substitution percentages show lower resistance to the penetration of CO_2. Furthermore, it is also likely that the use of RCA obtained from a higher number of recycling cycles also lowers the performance of concrete, since this kind of aggregates presents a higher quantity of adhered mortar.

In fact, as seen in Figure 12, the ranking of mixes with bigger penetration depths at 91 days is: C3100%; C2100%; C1100%; C325%; C225%; C125% and RC.

Figure 12 also shows that the speed of penetration of the carbonation front was higher in the first 7 days. However, contrary to what was stated by Yuan et al. (2010), in the case of this study it was not observed a decrease in the speed of penetration of the carbonation front over time.

It is also worth noting that at 28 days almost all mixes present a variation on the evolution of the carbonation depth. Since this behaviour was seen in all mixes except C3100% and no logical explanation was found, it is believed that an experimental anomaly may have occurred.

As seen by Figure 13, the excellent correlations obtained with the exponential asymptotic model demonstrates yet again the tendency of stabilization of the carbonation resistance with the increase of recycling cycles used to obtain the RCA. However, three recycling cycles were not enough to achieve a stabilization of this property.

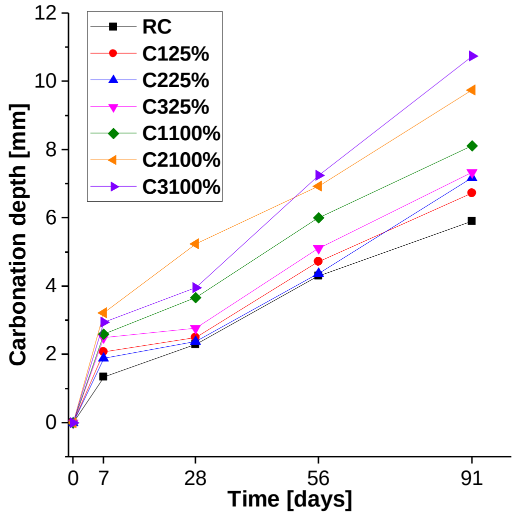


Figure 12 - Evolution of the carbonation depth over time

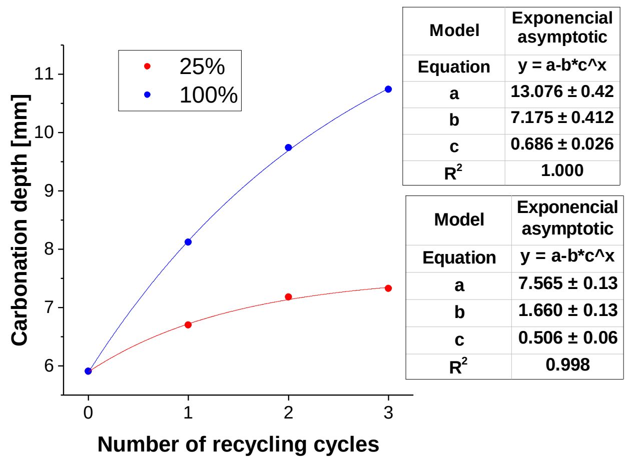


Figure 13 - Carbonation depth of mixes with 25% and 100% substitution of NCA as a function of the number of the recycling cycles of the RCA

3.3.5. Chloride penetration

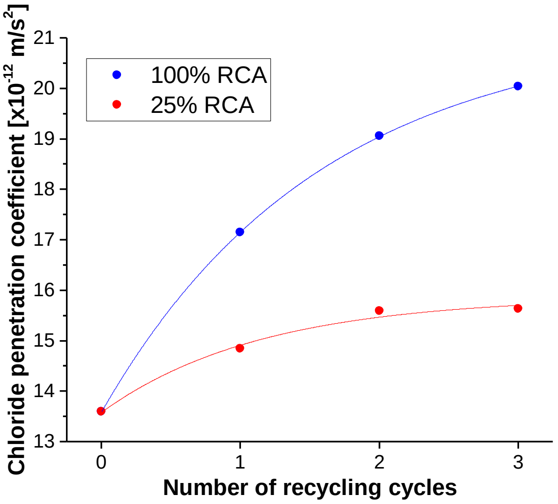
Table 7 presents the results obtained in the chloride penetration test. As expected the chloride penetration resistance decreases with the amount of NCA substitution. Also, the chloride penetration coefficient is higher for concrete mixes with RCA obtained from higher number of recycling cycles. As with other properties studied, the higher amount of adhered mortar is again the logical explanation for this result.

The results also show an increase of the chloride resistance from 28 to 91 days. Kou and Poon (2012) observed the same in their study and stated that a possible explanation was the higher volume of hydration products, which form impermeable regions and increase the resistance to the penetration of chloride ion.

Figure 14 and Figure 15 present the evolution of the chloride penetration coefficient as a factor of the number of recycling cycles of RCA for mixes at 28 and 91 days. Again, it is possible to note a stabilization tendency, which is corroborated by the very good correlations obtained with the exponential asymptotic model. Additionally, the results obtained for C325% at 28 and 91 days are within the error range of the asymptote (15.873 ± 0,273 m^2/s at 28 days; 15.296 ± 0,0,418 m^2/s at 91 days), which led to conclude that three recycling cycles were enough to stabilize this property for concretes produced with the incorporation of 25% of AGR.

Table 7 - Test results of the chloride penetration resistance

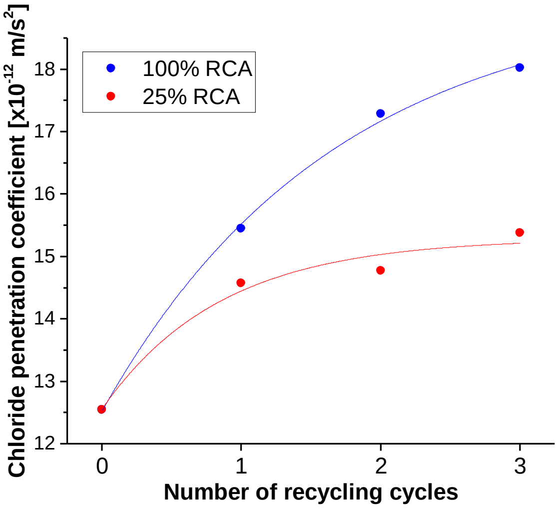
Average chloride penetration coefficient [$x10^{-12}$ m^2/s]				
Concrete	28 days	%(28 days) BR	91 days	%(91 days) BR
RC	13,60	-	12,55	-
C125%	14,85	6,5 %	14,57	16,1 %
C225%	15,59	14,6 %	14,77	17,7 %
C325%	15,64	15,0 %	15,38	22,5 %
C1100%	17,15	26,1 %	15,45	22,7 %
C2100%	19,06	40,1 %	17,29	37,8 %
C3100%	20,04	47,4 %	18,02	43,6 %



Substitution of NCA	100%
Equation	y = a-b*c^x
a	21,175 ± 0,052
b	7,577 ± 0,051
c	0,530 ± 0,005
R^2	1,000

Substitution of NCA	25%
Equation	y = a-b*c^x
a	15,873 ± 0,273
b	2,284 ± 0,292
c	0,419 ± 0,120
R^2	0,992

Figure 14 - Chloride diffusion coefficient at 28 days as a function of the number of recycling cycles of the RCA



Substitution of NCA	100%
Equation	y = a-b*c^x
a	19,176 ± 0,494
b	6,642 ± 0,482
c	0,549 ± 0,053
R^2	0,999

Substitution of NCA	25%
Equation	y = a-b*c^x
a	15,296 ± 0,418
b	2,731 ± 0,513
c	0,309 ± 0,194
R^2	0,975

Figure 15 - Chloride diffusion coefficient at 91 days as a function of the number of recycling cycles of the RCA

4. Conclusions

The aim of this dissertation was to study the influence of the incorporation of RCA obtained from multiple recycling of concrete on the durability performance of concrete. The following conclusions could be drawn:

- A higher number of recycling cycles generates RCA with higher amount of adhered mortar;
- Therefore, the use of these aggregates in the composition of concrete results in a lower durability performance;
- The increase of adhered mortar present in the constitution of RCA tends to stabilize given enough number of recycling cycles. This leads to an asymptotic behaviour of every property studied;
- Three recycling cycles were not enough to achieve a stabilization of the aggregates properties (apart from LA abrasion). However, some of the properties of the mixes made with this kind of RCA showed a stabilization at the end of a given number of recycling cycles.

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