# Durability and shrinkage performance of concrete made with coarse multi-recycled concrete aggregates

Stefano Silva[1], Luís Evangelista[2,4*] and Jorge de Brito[3,4]
[1]Master in Civil Engineering, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal, stefano_silva@live.com.
[2] Assistant Professor - Instituto Superior de Engenharia de Lisboa - IPL, R. Conselheiro Emídio Navarro, 1 - 1959-007 Lisbon, Portugal, evangelista@dec.isel.pt.
[3] Full Professor, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal, jb@civil.ist.utl.pt.
[4] CERIS-ICIST, Instituto Superior Técnico, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal.
* Corresponding author

**Abstract**

Since construction is one of the most environmental impacting activities in existence, it is important to study and develop solutions to make its processes more efficient. Thus, multiple-recycling of concrete presents itself as a possible alternative for the reutilization of construction and demolition waste (CDW) over a large period of time.

This paper presents the results and conclusions obtained from an extensive experimental campaign intended to study the durability performance of concrete made with aggregates resulting from multiple recycling cycles.

Concrete mixes with 25% and 100% of substitution of natural coarse aggregates with recycled coarse concrete aggregates obtained from one, two and three recycling cycles were produced.

Tests such as sieve analysis, water absorption, particle density, shape index, particle bulk density and Los Angeles abrasion were made to study the recycled coarse aggregates properties. Additionally, the workability and bulk density of fresh concrete were measured, and water absorption by immersion and capillarity, carbonation and chloride penetration were assessed to evaluate the durability performance of hardened concrete, as well as shrinkage.

The results obtained in the various tests show that, with the increase of recycling cycles, the recycled coarse aggregates demonstrate a quality decrease in their properties, resulting in a worse durability and shrinkage performance of the resulting concrete. Furthermore, it is shown that the decrease in performance tends to slow down with the increase of the recycling cycles, thus presenting an asymptotic behaviour. However, in most cases, it was not possible to establish that three recycling cycles were enough to stabilize the properties.

**Keywords:** concrete, coarse recycled aggregates, multiple recycling, durability, shrinkage, carbonation, chloride penetration, water absorption

## Introduction

### Literature review

Due to its high demand of natural resources and the amount of waste that it generates, construction is one of the most impactful activities to the environment. Waste generation in the construction industry is creating not only an environmental problem, but also a dumping-related logistics bottleneck [1]. According to Sandler [2], concrete and mixed rubble makes up for around 40% to 50% of the total volume of CDW generated in the USA. The dominant presence of this kind of debris make them a viable alternative for recycling and reutilisation as aggregates. Therefore, construction, as other economic activities, is increasingly forced to adjust its processes to achieve better environmental sustainability. To cope with this problem, a vast amount of studies on the structural and durability impact of the utilization of recycled aggregates (RA) on the production of concrete have been made in the last decades. However, most of these studies are limited to the use of recycled aggregates from one single recycling cycle. However, as this material use becomes a common practice worldwide, a new problem arises. These recycled concrete structures will eventually be demolished and new aggregates will be created. So far, it is not yet established how recycled aggregates form recycled source concrete will perform. Furthermore, it is still not known how sequential cycles of concrete recycling of concrete will affect the resulting aggregates. This paper intends to provide an initial overview on the durability performance of concrete.

### Aggregates properties

The main difference between natural aggregates (NA) and RA is that the latter are formed by both fragments of natural aggregates and attached old cement mortar [3]. The higher porosity, lower density and lower rigidity of the cement mortar directly affect the recycled aggregates properties and consequently the performance of the concrete produced with them. Due to the nature of the materials that constitute concrete produced with recycled aggregates (RAC), the process of multi-recycling amplifies these characteristics. In fact, the crushing procedure breaks the NA aggregates that are present in the RAC matrix in smaller fragments, originating RA with smaller particles of NA and a bigger quantity of attached mortar. Thomas et al. [4] used X-ray microtomography to determine the amount of adhered mortar in the recycled aggregates and concluded that it increases until the presence of the original natural aggregates is negligible, which is expected to happen by the fourth recycling cycle.

In accordance with this statement, Huda & Alam [5] found out that both the density and the bulk density of the RA assumed lower values as the number of recycling cycles increased, corroborating the percentual increase of adhered mortar in the RA. Similar results were obtained by Zhu et al. [6]. A higher quantity of adhered mortar results in a more porous material which facilitates fluids' penetration. Hence, it is only natural that RA present a much higher water absorption with the increasing amount of adhered mortar [3]. Both Huda & Alam [5] and de Brito et al [7] observed increasing water absorption capacity with higher number of recycling cycles. However, the evolution of the water absorption by the RA does not follow a linear behaviour. In fact, most of the water absorption capacity was exhausted in the first 10 minutes [8, 9].

The water/cement ratio of the source concrete has a significant influence on the quality of the RA obtained [10]. Source concrete with lower w/c in general presents a higher mechanical strength and lower porosity, resulting in RA of better quality and higher mechanical resistance [11-13].

Although the shape of the RA is fundamentally defined by the crushing process [14]. This kind of aggregates tends to present a more angular shape then their natural counterpart [9, 15], mainly affecting the workability of fresh concrete [5].

Concrete properties

According to studies done on the substitution of natural aggregates with recycled coarse aggregates to produce concrete, both the durability and mechanical properties of concrete are affected. However, it is generally agreed that the use of recycled aggregates has a bigger impact on the durability performance. The use of a more porous aggregate results in a more porous concrete matrix, hence increasing its fluid penetration capacity [16-18]. According to Olorunsogo e Padayachee [19], not only this property presents a linear behaviour according to the percentage of RA incorporated in the concrete mix, but it is also directly influenced by the curing time of concrete. In fact, concrete with a higher curing time showed a significant decrease of the water absorption capacity.

That same porosity is the main cause of the diminishing resistance to corrosion-related processes like carbonation and chloride penetration. Moreover, the incorporation of recycled aggregates results in a worse performance of concrete in terms of carbonation resistance [20-22]. A similar behaviour was found for chloride penetration resistance [20, 23].

Additionally, the lower stiffness presented by the attached mortar that constitutes the RA results in a lower density [9, 24-26] and stiffness of the concrete's matrix. Because of this, concrete produced with recycled aggregates generally presents a much higher shrinkage than that of conventional concrete. However, the use of recycled aggregates of higher quality can have a big impact on limiting this problem [27, 28]. It is also worth noting that the shrinkage presented by RAC tends to follow a linear evolution in accordance with the percentage of substitution of NA with RA [29].

It can be concluded that the reason for the worse durability performance of recycled aggregate concrete is its bigger porosity, which is directly related to the attached mortar that constitutes the RA. Consequently, since the process of multiple recycling it is expected to produce recycling aggregates with an increasing amount of attached mortar, it is likely that the mixes under study will demonstrate a lowering durability performance and higher shrinkage, in accordance to the higher amount of recycling cycles that originated the RA that constitutes them.

To the authors' best knowledge, research made on recycled aggregate concrete from multiple recycling has mainly focused on the mechanical properties. Moreover, these previous researches used RA obtained from several origins and, consequently, with different properties. The innovation of this research lies on the determination of durability properties of RAC made with RA from multiple recycling steps, which were produced from crushing an original concrete with the same mix design and properties of the reference concrete, thus eliminating entropy resulting from this parameter. Each new RAC was made with RA from a previous recycling cycle of a concrete made exactly with the same composition and constituents as the cycle before, only changing the origin of the RA.

## Methodology

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

The first phase consists of the production 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 (SCI, SCII, SCIII) and later crushed with the help of a jaw crusher. The first source concrete (SCI) was made only with natural aggregates. Both SCII and SCIII were produced with a 100% substitution of natural coarse aggregates with recycled coarse aggregates obtained from the previous cycle.

In the second phase, seven more mixes were produced: a reference concrete, three mixes with 25% and three more with 100% substitution of natural coarse aggregates (NCA) with recycled coarse aggregates (RCA). Just like the SCI, a reference concrete (RC) was produced exclusively with natural aggregates. On the other hand, to produce the mixes with 25% and 100% substitution of NCA, RCA from one (C1-25%, C1-100%), two (C2-25%, C2-100%) and three (C3-25%, C3-100%) recycling cycles were used. Figure 1 presents a schematic diagram of the methodology described.

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

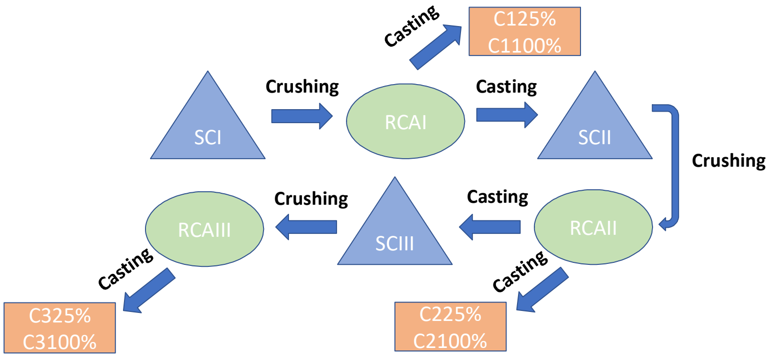



Figure 1 - Schematic diagram of the methodology used to produce all concrete mixes

## Experimental campaign

### Materials

Coarse and fine natural were used in the production of the concrete mixes, as well as coarse recycled concrete aggregates. The natural aggregates included silica sand and crushed limestone gravel. The recycled coarse aggregates were obtained from multiple recycling of concrete with a design strength of 30 MPa in each cycle. Overall, three cycles of recycling were made. Type I cement of class 42.5R and tap water were used in the production of all mixes.

### Concrete composition

To enable establishing a good comparison between all concrete mixes, a slump interval of 125 ± 15 mm was kept constant for all tested mixes, which approximately corresponds to the average of the S3 slump class [30].

Because of the higher water absorption shown by the recycled aggregates, and taking into consideration the conclusions about the disadvantages of the pre-saturation method [31-36], an adaptation of the method suggested by Rodrigues et al. [37] was used in this study.

This 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 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 (total) w/c is defined as the ratio between the water and cement including the water necessary to compensate the recycled coarse aggregates' absorption. For these concrete mixes, water compensation was made considering the amount of water that is potentially absorbed during the batch duration, which was set at 15 minutes.

To eliminate entropy factors in the results, all the aggregates utilized were oven-dried and then cooled down to room temperature before use. The coarse aggregates were mechanically sieved in the following particle size intervals: 4-5.6 mm, 5.6-8 mm, 8-11.2 mm, 11.2-16 mm, 16-22.4 mm, and then stored in containers to prevent humidity exchange with the environment. For each concrete mix, the RA grading curve was systematically constructed so that it would replicate the NA grading curve. This served two purposes: first, using the same optimized grading curve for NA and RA enabled to always produce concrete mixes with the smallest theoretical void content; additionally, by doing this, the grading curves of the aggregates at different recycling cycles were constant, removing the influence of this parameter from the analysis of the mixes' behaviour.

All the mixes were designed in accordance with the Faury's method [38], 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. Furthermore, the substitution of NA with RA was made by volume. In fact, since the density of RA decreases as the number of recycling cycles increases, a substitution by mass would generate a higher volume of aggregates per measure of volume, and consequently affect the solid particle content of the concrete mix. Table 1 presents the composition of the components of all concrete mixes tested.

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

| Components | # [mm] | RC | C1-25% | SCI & C1-100% | C2-25% | SCII & C2-100% | C3-25% | SCIII & C3-100% |
|---|---|---|---|---|---|---|---|---|
| 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 | - | 21.7 | 86.8 | 20.3 | 81.3 | 19.9 | 79.4 |
| | 5.6-8 | - | 24.0 | 95.9 | 22.4 | 89.9 | 22.0 | 87.8 |
| | 8-11.2 | - | 25.9 | 103.4 | 24.2 | 97.0 | 23.7 | 94.8 |
| | 11.2-16 | - | 73.0 | 293.3 | 68.4 | 274.0 | 66.9 | 267.7 |
| | 16-22.4 | - | 73.0 | 292.2 | 68.4 | 274.0 | 66.9 | 267.7 |
| 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 |

## Aggregate testing

To determine the aggregates properties, several tests were performed. The size grading analysis followed the NP EN 933-1 [39] and NP EN 933-2 [40] procedures. The density and water absorption were determined according to NP EN 1097-6 [41]. The NP EN 1097-3 [42] procedure was used to determine the bulk density. The Los Angeles abrasion test was performed according to NP EN 1097-2 [43] and the shape index was determined according to the NP EN 933-4 [44] standard. Finally, all the samples tested were prepared according to the percentage of each aggregate's size in concrete.

## Concrete testing

All mixes were tested in the fresh state for workability and density according to the NP EN 12350-2 [45] and NP EN 12350-6 [46] standards respectively. In the hardened state, concrete mixes were subjected to a variety of tests to determine their properties.

Even though this study focuses on the durability properties of concrete, it is fundamental to evaluate the compressive strength resistance to have an idea of the quality of concrete. Tests were performed on three 150 mm cubic samples for each mix at the ages of 7, 28 and 56 days in accordance to NP EN 12390-3 [47].

Regarding the durability performance, water absorption by immersion was determined in three 100 mm cubic specimens per mix according to LNEC E394 [48]. The evaluation of the water absorption by capillary was made according to LNEC E393 [49]. The procedure consists in dipping three different cylindrical samples with diameter of 150 mm and height of 100 mm in 5 ± 1 mm layer of water. The samples were then weighted after 3, 6, 24 and 72 hours after the first contact with the water to evaluate the amount of water absorbed during that time frame.

To determine the shrinkage performance of each mix, two 150 x 150 x 600 mm samples were subjected to controlled humidity (50 ± 5%) and temperature conditions (20 ± 2 ºC) for a total of 91 days according to LNEC E398 [50], starting at 24 ± 1 h after casting. To take in consideration the nonlinear shrinkage behaviour of concrete, the time intervals of the measurements were adjusted according to the age of the sample.

To determine the carbonation resistance of each concrete mix the LNEC E391 [51] standard was followed. Tests were performed on specimens that were exposed to a controlled $CO_2$ concentration (5%), humidity and temperature environment during 7, 28, 56 and 91 days. In total, two specimens for each age were tested, making a grand total of 8 specimens for each mix.

The chloride penetration test was performed on three specimens per mix in accordance to the LNEC E463 [52] standard, which consists in a non-stationary accelerated migration test that intends to determine the chloride diffusion coefficient of concrete.

## Results and discussion

### Aggregates properties results

The determination of the aggregates' properties is fundamental to understand and correctly evaluate the performance of the concrete mixes produced with them. Table 2 presents all the results obtained from the tests performed. According to these results, it can be concluded that in general the quality of RCA is lower than that of NCA. Additionally, it is noted that in general the properties of the aggregate decay 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 [3]. In fact, as the recycling cycles proceed, the quantity of adhered mortar also increases, consequently reducing the recycled aggregates' quality [5]. Since aggregates are a major constituent of concrete, it is expected that the mixes produced may show similar behaviour.

Table 2 - 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 (24 h) [%]** | 1.09 | 5.64 | 7.95 | 9.64 |
| **LA abrasion [%]** | 27.93 | 38.81 | 41.18 | 40.89 |
| **Shape index [%]** | 18 | 18 | 19 | 18 |

However, as shown by the results, most of the properties studied present an asymptotic behaviour with the number of recycling cycles. This may indicate that the quantity of adhered mortar that is part of the recycled aggregate composition tends to stabilize at the end of a given number of cycles. This asymptotic behaviour means that there is a lower limit to the densities of the RA aggregates, regardless of the number of recycling cycles. The same logic may be applied to the water absorption of RA, establishing an upper limit value of this property.

The evolution of water absorption through time is illustrated in Figure 2. The curve for CRA from cycles 1 to 3 shows that the hydrodynamic flow of water within the RA depends on the recycling cycle. It seems that, as the number or recycling cycles increase, so does the time required to reach a certain level of water absorption. That may be related with the fact that the number and length of capillaries and macro voids increase, making it harder to fill in a given time interval. That is also clear upon analysing Table 3, that shows the percentage of water (relative to the maximum, at 24h) that is absorbed at a given time interval.

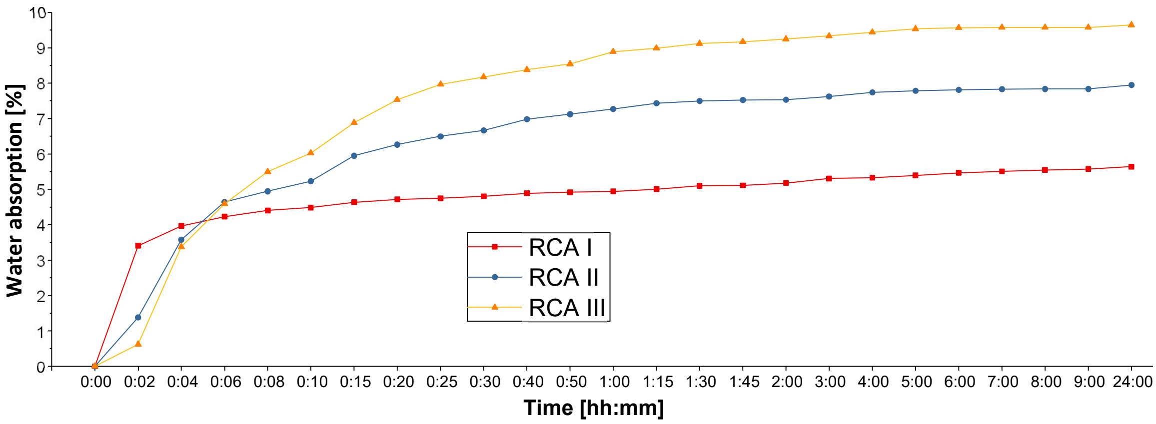



Figure 2 - Water absorption with time

Table 3 - Water absorption relative to maximum at 24 hours

| Time interval | Water absorption relative to maximum [%] | | |
|---|---|---|---|
| | RCA I | RCA II | RCA III |
| 6 min | 75.0 | 58.4 | 47.6 |
| 10 min | 79.5 | 65.8 | 62.5 |
| 15 min | 82.2 | 74.8 | 71.4 |
| 30 min | 85.2 | 83.8 | 84.8 |
| 24 h | 100 | 100 | 100 |

Fresh concrete results

The concrete workability and density were tested in the fresh state. As stated, the goal was for all mixes to present approximately the same workability, within the 125 ± 15 mm slump interval. However, contrary to what was observed by Huda & Alam [5], no relevant loss of workability of the mixes that included aggregates from higher recycling cycles was noted. A possible explanation is the similar shape index presented by the NCA and RCA (Table 2).

The fresh density results (Table 4) followed the same asymptotic behaviour as the density of the recycled coarse aggregates (Figure 3). In fact, an excellent linear correlation can be established between the two parameters (Figure 4). Also, because of the lower density presented by the RCA, higher percentages of substitution of NCA result in lower density values of fresh concrete.

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

| Fresh concrete density [kg/m$^3$] | RC | C1-100% | C1-25% | C2-100% | C2-25% | C3-100% | C3-25% |
|---|---|---|---|---|---|---|---|
| Average | 2413.80 | 2319.30 | 2385.30 | 2279.80 | 2383.80 | 2264.80 | 2375.80 |

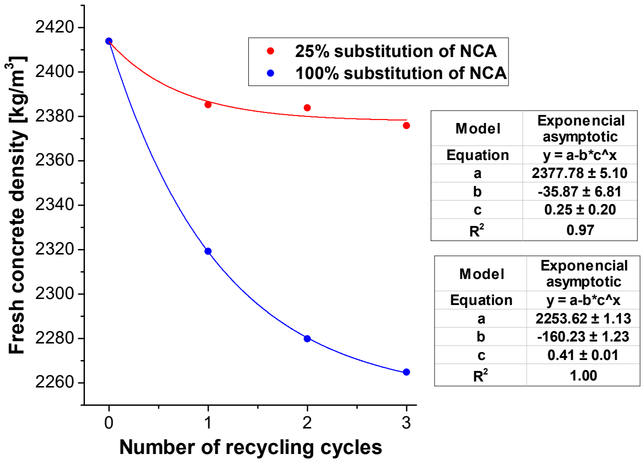



Figure 3 - Concrete fresh density *versus* number of recycling cycles of RCA

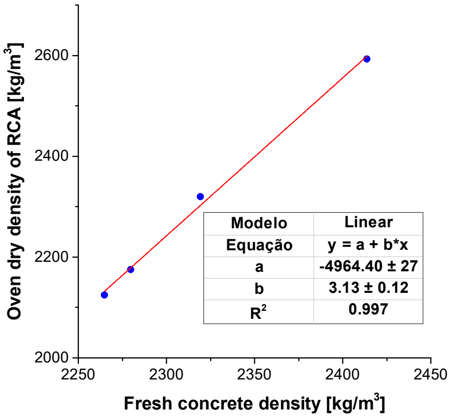



Figure 4 - Correlation between RCA oven dry density and fresh density of concrete mixes with 100% substitution of NCA

## Hardened concrete properties

### Compressive strength

The results to the compressive strength tests (Table 5) show that in all ages the mixes with 100% RCA showed a lower compressive strength than RC, which is explained by the presence of adhered mortar in the constitution of RCA [18]. Also, the higher the recycling cycles of 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 C3-25% mix was always lower than that of the RC. This may suggest that this property is not significantly influenced by low percentages of incorporation of RCA. The results prove that, as the number of cycles of recycling of CRCA increases, there is an asymptotic decrease of the compressive strength of the mixes made with them. This trend is because CRCA have a more porous structure, which weakens the mechanical behaviour.

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 |
| **C1-25%** | 47.6 | 59.7 | 65.0 |
| **C2-25%** | 47.0 | 55.9 | 60.7 |
| **C3-25%** | 45.2 | 55.9 | 62.7 |
| **C1-100%** | 44.0 | 54.1 | 59.0 |
| **C2-100%** | 43.3 | 53.3 | 57.6 |
| **C3-100%** | 40.3 | 48.6 | 56.2 |

### Shrinkage

The results show that 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

[9, 24-26]. In fact, the bigger the quantity of adhered mortar that is part of 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 from a higher number of recycling cycles. As seen in Figure 5, the evolution of shrinkage deformation in all mixes presents a non-linear behaviour. As expected, it is much more relevant in the first ages than in the older ones. Additionally, until 7 days 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 [53]. The phenomena of internal curing has been discussed thoroughly, especially in concrete made with lightweight aggregates [54-57], and has shown that systematic and continuous water supply to the matrix by the porous aggregates (such as lightweight) can significantly reduce internal stress in the concrete structure, reducing autogenous shrinkage. It can also be stated that until 91 days of duration of the test the different concrete mixes did not achieve a stabilization of the deformation by shrinkage (Figure 6).

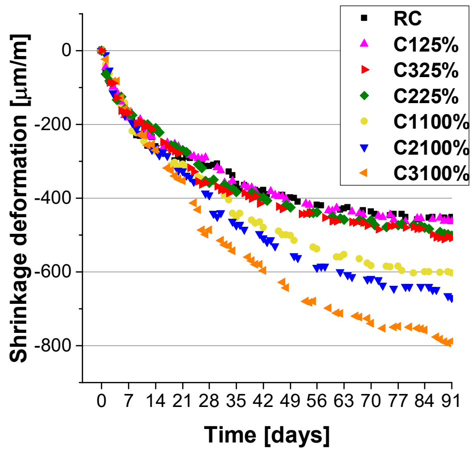



Figure 5 - Evolution of shrinkage deformation over time

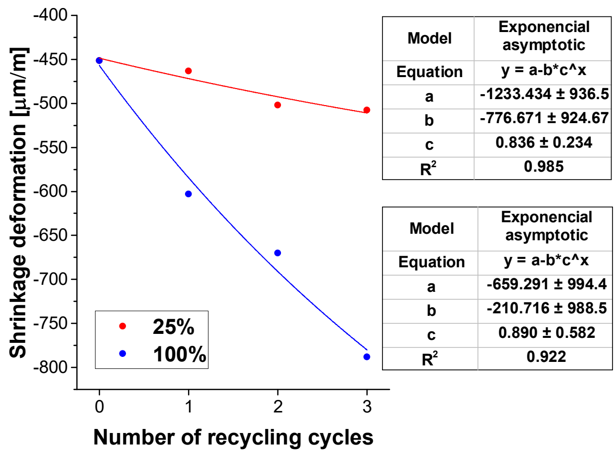



Figure 6 - Shrinkage deformation at 91 days for mixes with 25% and 100% substitution of NCA *versus* number of recycling cycles of RCA

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 evolution of these properties with the number of recycling cycles can also be seen in Figures 7 and 8, respectively. Both of these properties are associated with concrete porosity, which is translated by the number of voids present in its matrix. Since RCA present a much higher porosity and water absorption capacity than NA, it is expected that RCA show higher values of water by immersion and capillarity. The results support this theory, since every mix that incorporates recycled aggregates presents a bigger water absorption than 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 resulting concrete. 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 2).

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

| Concrete | Water absorption by capillary (72 h) [x $10^{-3}$ g/mm$^2$] | % RC | Water absorption by immersion [%] | % RC |
|---|---|---|---|---|
| **RC** | 3.43E-03 | - | 13.45 | - |
| **C1-25%** | 5.84E-03 | 70.26 | 15.26 | 13.46 |
| **C2-25%** | 6.25E-03 | 82.22 | 15.69 | 16.65 |
| **C3-25%** | 6.57E-03 | 91.55 | 16.06 | 19.41 |
| **C1-100%** | 7.53E-03 | 119.53 | 18.60 | 38.29 |
| **C2-100%** | 9.21E-03 | 168.51 | 21.67 | 61.12 |
| **C3-100%** | 10.70E-03 | 211.95 | 21.72 | 61.49 |

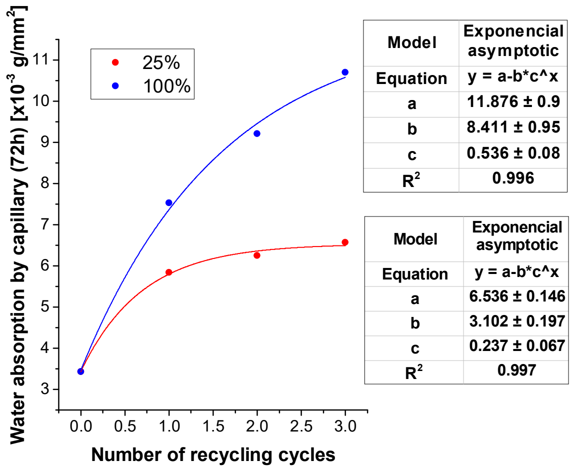



Figure 7 - Capillary absorption of mixes with 25% and 100% substitution of NCA *versus* number of the recycling cycles of RCA

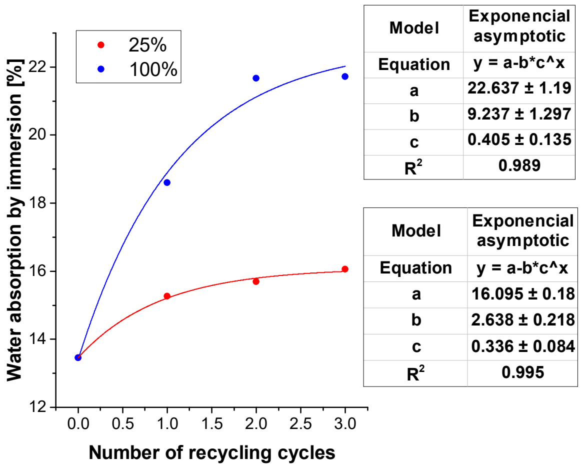



Figure 8 - Water absorption by immersion of mixes with 25% and 100% substitution of NCA *versus* number of the recycling cycles of RCA

## 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 resulting 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 10, the ranking of mixes with bigger penetration depths at 91 days is: C3-100% (highest); C2-100%; C1-100%; C3-25%; C2-25%; C1-25% and RC (lowest).

Figure 9 also shows that the penetration rate of the carbonation front was higher in the first 7 days. However, contrary to what was stated by Yuan et al. [22], in this study no decrease in the speed of penetration of the carbonation front over time was observed.

It is also worth noting that at 28 days almost all mixes present a variation on the evolution of the carbonation depth, with the exception of the C3-100% mix, which may be due to some experimental anomaly.

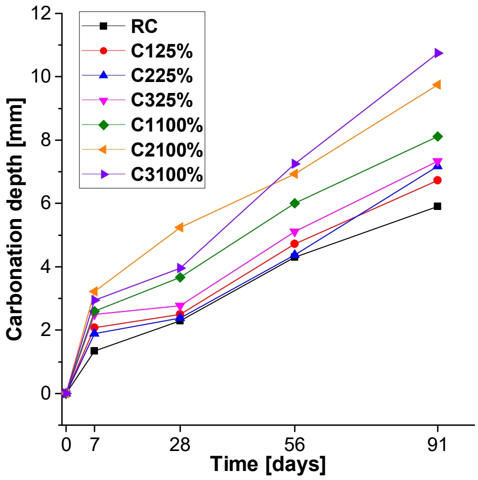



Figure 9 - Evolution of the carbonation depth over time

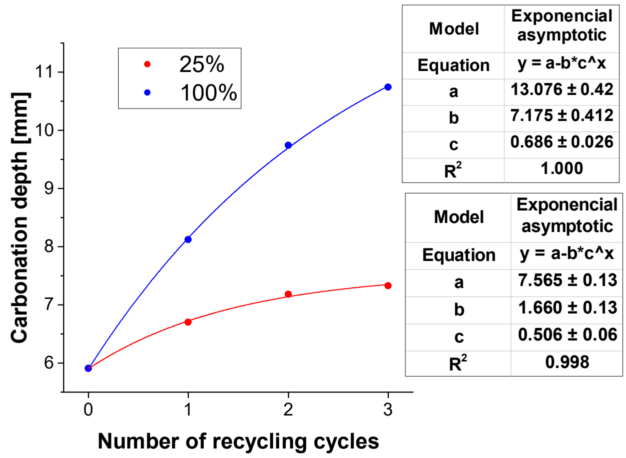



Figure 10 - Carbonation depth of mixes with 25% and 100% substitution of NCA *versus* number of the recycling cycles of RCA

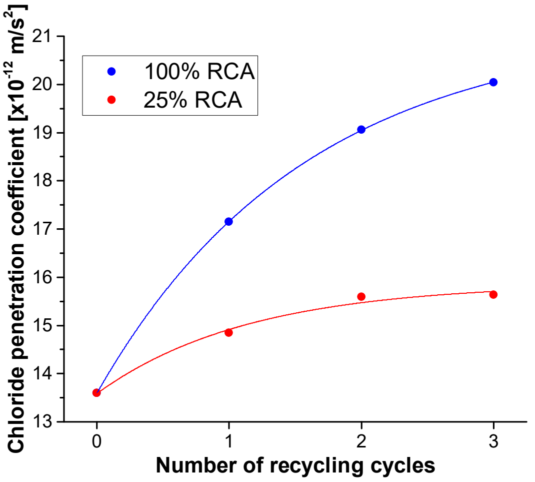
Chloride penetration

Table 7 presents the results from the chloride penetration test. As expected, the chloride penetration resistance decreases with the NCA substitution ratio. Also, the chloride penetration coefficient is higher for concrete mixes with RCA resulting from higher number of recycling cycles (Figures 11 and 12, for 28 and 91 days, respectively). As with other properties studied, the higher amount of adhered mortar is again the logical explanation of this result.

The results also show an increase of the chloride resistance from 28 to 91 days. Kou & Poon [20] 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.

Table 7 - Test results of the chloride penetration resistance

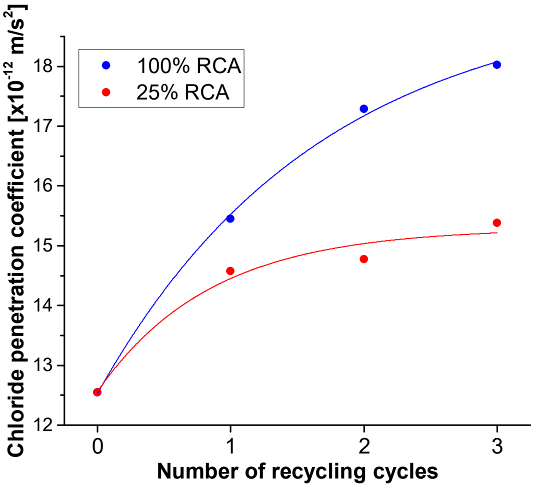
| **Average chloride penetration coefficient [x10$^{-12}$ m$^2$/s]** | | | | |
|---|---|---|---|---|
| **Concrete** | 28 days | %(28 days) $_{BR}$ | 91 days | %(91 days) $_{BR}$ |
| **RC** | 13,60 | - | 12,55 | - |
| **C1-25%** | 14,85 | 6,5 % | 14,57 | 16,1 % |
| **C2-25%** | 15,59 | 14,6 % | 14,77 | 17,7 % |
| **C3-25%** | 15,64 | 15,0 % | 15,38 | 22,5 % |
| **C1-100%** | 17,15 | 26,1 % | 15,45 | 22,7 % |
| **C2-100%** | 19,06 | 40,1 % | 17,29 | 37,8 % |
| **C3-100%** | 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 11 - Chloride diffusion coefficient at 28 days *versus* number of recycling cycles of 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 12 - Chloride diffusion coefficient at 91 days *versus* number of recycling cycles of RCA

**Influence of the number of recycling cycles on the properties of hardened concrete**

As shown in section 3, most of the hardened concrete properties follow a tendency of stabilization if enough recycling cycles are performed. However, are three recycling cycles enough to expect that a defined property will not present significant variations if further recycling cycles are done? To answer this, correlation studies involving the exponential asymptotic model were done for all properties.

As seen in Figure 6, good correlations factors have been obtained with the use of an exponential asymptotic model of the shrinkage behaviour of concrete. However, as corroborated by the unacceptable large error intervals of the asymptotes obtained, three recycling cycles are not enough to reach a stabilization of this property.

Similar results have been obtained for the carbonation resistance study. As seen in Figure 10, yet again the model demonstrates a tendency of stabilization of this property with the increase of recycling cycles used to obtain the RCA. However, as observed for shrinkage, three recycling cycles were not enough to achieve a stabilization.

The water absorption by capillary of the mixes with 25% and 100% substitution of NCA presents an asymptotic behaviour regarding the number of recycling cycles (Figure 7Figure 7). This is also the case for the water absorption by immersion (Figure 8). Furthermore, since the result obtained for the water absorption by immersion for the C3-25% (16.06%) and C3-100% (21.72%) mixes are within the error range of the asymptotes given by the 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 C3-25% (6.57x10-3) also is inside the error range of asymptote ($6,536 \times 10^{-3} \pm 0,146 \times 10^{-3}$).
Regarding the evolution of the chloride penetration coefficient, Figures 11 and 12 present the evolution of this property as a function of the number of recycling cycles of RCA for mixes at 28 and 91 days. The results obtained for C3-25% 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 achieve stabilization for mixes produced with incorporation of 25% of RA.

**Conclusions**

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

- A higher number of recycling cycles generates RCA with higher adhered mortar content;
- 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 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 three or less recycling cycles.

**Acknowledgements**

The authors gratefully acknowledge the support of the Portuguese Foundation for Science and Technology (Fundação para a Ciência e Tecnologia) through the research project PTDC/ECI-CON/29196/2017 (RInoPolyCrete) and CERIS Research Institute, Instituto Superior Técnico, Universidade de Lisboa, in the framework of project UIDB/04625/2020.

**References**

[1] B. A. G. Bossink and H. J. H. Brouwers, "Construction Waste: Quantification and Source Evaluation", J. Constr. Eng. Manag., vol. 122, no. 1, pp. 55–60, Mar. 1996.

[2] K. Sandler, "Analyzing what's recyclable in C&D debris", Biocycle, vol. 44, no. 11, pp. 51–54, 2003.

[3] M. S. de Juan and P. A. Gutiérrez, “Study on the influence of attached mortar content on the properties of recycled concrete aggregate”, Constr. Build. Mater., vol. 23, no. 2, pp. 872–877, Feb. 2009.

[4] C. Thomas, J. de Brito, V. Gil, J. A. Sainz-Aja, and A. Cimentada, “Multiple recycled aggregate properties analysed by X-ray microtomography”, Constr. Build. Mater., vol. 166, pp. 171–180, Mar. 2018.

[5] S. B. Huda and M. S. Alam, “Mechanical behavior of three generations of 100% repeated recycled coarse aggregate concrete”, Constr. Build. Mater., vol. 65, pp. 574–582, Aug. 2014.

[6] P. Zhu, X. Zhang, J. Wu, and X. Wang, “Performance degradation of the repeated recycled aggregate concrete with 70% replacement of three-generation recycled coarse aggregate”, J. Wuhan Univ. Technol. Sci. Ed., vol. 31, no. 5, pp. 989–995, Oct. 2016.

[7] J. de Brito, A. P. Gonçalves, and J. R. dos Santos, “Recycled concrete production. Multiple recycling of concrete coarse aggregates”, Rev. Ing. Construcción, vol. 21, no. 1, pp. 33–40, Nov. 2006.

[8] M. S. de Juan, “Study on the use of recycled aggregate in structural concrete production”, Universidad Politécnica de Madrid, 2004.

[9] N. Fonseca, J. de Brito, and L. Evangelista, “The influence of curing conditions on the mechanical performance of concrete made with recycled concrete waste”, Cem. Concr. Compos., vol. 33, no. 6, pp. 637–643, 2011.

[10] T. C. Hansen and H. Narud, “Strength of recycled concrete made from crushed concrete”, Concr. Int., vol. 5, no. 1, pp. 79–83, 1983.

[11] M. Casuccio, M. C. Torrijos, G. Giaccio, and R. Zerbino, “Failure mechanism of recycled aggregate concrete”, Constr. Build. Mater., vol. 22, no. 7, pp. 1500–1506, Jul. 2008.

[12] C. J. Zega, Y. A. Villagrán-Zaccardi, and A. A. Di Maio, “Effect of natural coarse aggregate type on the physical and mechanical properties of recycled coarse aggregates”, Mater. Struct., vol. 43, no. 1–2, pp. 195–202, Jan. 2010.

[13] T. Yoshikane, “Present status of recycling waste cement concrete in Japan, Private Communication Research Laboratory”, Tokyo, 1988.

[14] M. Martín-Morales, M. Zamorano, A. Ruiz-Moyano, and I. Valverde-Espinosa, “Characterization of recycled aggregates construction and demolition waste for concrete production following the Spanish Structural Concrete Code EHE-08”, Constr. Build. Mater., vol. 25, no. 2, pp. 742–748, Feb. 2011.

[15] J. P. B. Vieira, J. R. Correia, and J. de Brito, “Post-fire residual mechanical properties of concrete made with recycled concrete coarse aggregates”, Cem. Concr. Res., vol. 41, no. 5, pp. 533–541, May 2011.

[16] A. Katz, “Properties of concrete made with recycled aggregate from partially hydrated old concrete”, Cem. Concr. Res., vol. 33, no. 5, pp. 703–711, May 2003.

[17] M. Malešev, V. Radonjanin, and S. Marinković, “Recycled Concrete as Aggregate for Structural Concrete Production”, Sustainability, vol. 2, no. 5, pp. 1204–1225, Apr. 2010.

[18] W. H. Kwan, M. Ramli, K. J. Kam, and M. Z. Sulieman, “Influence of the amount of recycled coarse aggregate in concrete design and durability properties”, Constr. Build. Mater., vol. 26, no. 1, pp. 565–573, Jan. 2012.

[19] F. . Olorunsogo and N. Padayachee, “Performance of recycled aggregate concrete monitored by durability indexes”, Cem. Concr. Res., vol. 32, no. 2, pp. 179–185, Feb. 2002.

[20] S. C. Kou and C. S. Poon, “Enhancing the durability properties of concrete prepared with coarse recycled aggregate”, Constr. Build. Mater., vol. 35, pp. 69–76, Oct. 2012.

[21] J. Xiao, B. Lei, and C. Zhang, “On carbonation behavior of recycled aggregate concrete”, Sci. China Technol. Sci., vol. 55, no. 9, pp. 2609–2616, Apr. 2012.

[22] C. Yuan, Z. Luo, T. Ding, H. Wang, Y. Hao, and H. Zhan, “Orthogonal Experiment of Carbonation Resistance for Recycled Aggregate Concrete”, Technol. - Mater. Sci. Ed., vol. 21, pp. 9–12, 2010.

[23] M. Chakradhara Rao, S. K. Bhattacharyya, and S. V. Barai, “Influence of field recycled coarse aggregate on properties of concrete”, Mater. Struct., vol. 44, no. 1, pp. 205–220, Jan. 2011.

[24] M. Gomes and J. de Brito, “Structural concrete with incorporation of coarse recycled concrete and ceramic aggregates: durability performance”, Mater. Struct., vol. 42, no. 5, pp. 663–675.

[25] F. López-Gayarre, P. Serna, A. Domingo-Cabo, M. A. Serrano-López, and C. López-Colina, “Influence of recycled aggregate quality and proportioning criteria on recycled concrete properties”, Waste Manag., vol. 29, no. 12, pp. 3022–3028, Dec. 2009.

[26] Á. Salesa et al., “Physico – mechanical properties of multi – recycled concrete from precast concrete industry”, J. Clean. Prod., vol. 141, pp. 248–255, Jan. 2017.

[27] K. Yanagibashi, T. Yonezawa, K. Arakawa, and M. Yamada, “A new concrete recycling technique for coarse aggregate regeneration process”, in Challenges of Concrete Construction: Volume 5, Sustainable Concrete Construction, Thomas Telford Publishing, 2002, pp. 511–522.

[28] K. Yang, H. Chung, and A. Ashour, “Influence of type and replacement level of recycled aggregates on concrete properties”, ACI Mater. J., vol. 105, no. 3, pp. 289–296, 2008.

[29] R. V Silva, J. de Brito, and R. K. Dhir, “Prediction of the shrinkage behavior of recycled aggregate concrete: A review”, Constr. Build. Mater., vol. 77, pp. 327–339, Feb. 2015.

[30] CEN, EN 206-1:2013 - Concrete - Specification, performance, production and conformity. Brussels: Comité Européen de Normalisation, 2013.

[31] L. Ferreira, J. de Brito, and M. Barra, “Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties”, Mag. Concr. Res., vol. 63, no. 8, pp. 617–627, Aug. 2011.

[32] S. C. Kou and C. S. Poon, “Properties of self-compacting concrete prepared with coarse and fine recycled concrete aggregates”, Cem. Concr. Compos., vol. 31, no. 9, pp. 622–627, Oct. 2009.

[33] M. Pepe, R. D. Toledo Filho, E. A. B. Koenders, and E. Martinelli, “Alternative processing procedures for recycled aggregates in structural concrete”, Constr. Build. Mater., vol. 69, pp. 124–132, Oct. 2014.

[34] P. Amorim, J. De Brito, and L. Evangelista, “Concrete made with coarse concrete aggregate: Influence of curing on durability”, ACI Mater. J., vol. 109, no. 2, pp. 195–204, 2012.

[35] V. W. Y. Tam, X. F. Gao, C. M. Tam, and C. H. Chan, “New approach in measuring water absorption of recycled aggregates”, Constr. Build. Mater., vol. 22, no. 3, pp. 364–369, Mar. 2008.

[36] V. W. Y. Tam, C. M. Tam, and Y. Wang, “Optimization on proportion for recycled aggregate in concrete using two-stage mixing approach”, Constr. Build. Mater., vol. 21, no. 10, pp. 1928–1939, Oct. 2007.

[37] F. Rodrigues, L. Evangelista, and J. de Brito, “A new method to determine the density and water absorption of fine recycled aggregates”, Mater. Res., vol. 16, no. 5, pp. 1045–1051, 2013.

[38] J. Faury and A. Caquot, Le Béton, 3rd ed. Paris, France: Dunod, 1958.

[39] IPQ, NP EN 933-1: 2000. Ensaios das propriedades geométricas dos agregados. Parte 1: Análise granulométrica. Método de peneiração. Caparica, Portugal: Instituto Português da Qualidade, 2000.

[40] IPQ, NP EN 933-2: 1999. Ensaios para determinação das características geométricas dos agregados. Parte 2: determinação da distribuição granulométrica. Peneiros de ensaio, dimensão nominal das aberturas. Caparica, Portugal: Instituto Português da Qualidade, 1999.

[41] IPQ, NP EN 1097-6: 2003/A1 2010. Ensaios das propriedades mecânicas e físicas dos agregados. Parte 6: Determinação da massa volúmica e da absorção de água. Caparica, Portugal: Instituto Português da Qualidade, 2010.

[42] IPQ, NP EN 1097-3: 2002. Ensaios das propriedades mecânicas e físicas dos agregados. Parte 3: Determinação da baridade e do volume de vazios. Caparica, Portugal: Instituto Português da Qualidade, 2002.

[43] IPQ, NP EN 1097-2: 2011. Ensaios das propriedades mecânicas e físicas dos agregados. Parte 2: Métodos para a determinação da resistência à fragmentação. Caparica, Portugal: Instituto Português da Qualidade, 2011.

[44] IPQ, NP EN 933-4: 2002. Ensaios geométricos dos agregados. Parte 4: Determinação da forma das partículas - Índice de forma. Caparica, Portugal: Instituto Português da Qualidade, 2002.

[45] IPQ, NP EN 12350-2: 2009. Ensaios do betão fresco. Parte 2: Ensaio de abaixamento. Caparica, Portugal: Instituto Português da Qualidade, 2009.

[46] IPQ, NP EN 12350-6: 2009. Ensaios do betão fresco. Parte 6: Massa volúmica. Caparica, Portugal: Instituto Português da Qualidade, 2009.

[47] IPQ, NP EN 12390-3: 2009. Ensaios do betão endurecido. Parte 3: Resistência à compressão de provetes. Caparica, Portugal: Instituto Português da Qualidade, 2009.

[48] LNEC, E 394-1993. Betões. Determinação da absorção de água por imersão. Ensaio à pressão atmosférica. Lisboa, Portugal: Laboratório Nacional de Engenharia Civil, 1993.

[49] LNEC, E 393-1993. Betões. Determinação da absorção de água por capilaridade. Lisboa, Portugal: Laboratório Nacional de Engenharia Civil, 1993.

[50] LNEC, E 398-1993. Betões. Determinação da retracção e expansão. Lisboa, Portugal: Laboratório Nacional de Engenharia Civil, 1993.

[51] LNEC, E 391-1993. Betões. Determinação da resistência à carbonatação. Lisboa, Portugal: Laboratório Nacional de Engenharia Civil, 1993.

[52] LNEC, E 463-2004. Betões. Determinação do coeficiente de difusão dos cloretos por ensaio de migração em regime não estacionário. Lisboa, Portugal: Laboratório Nacional de Engenharia Civil, 2004.

[53] A. E. B. Cabral, V. Schalch, and D. Molin, “Shrinkage modeling for recycled aggregate concretes”, Ibracon Struct. Mater. J., vol. 3, no. 1, pp. 1–23, 2010.

[54] A. Bentur, S. Igarashi, and K. Kovler, “Prevention of autogenous shrinkage in high-strength concrete by internal curing using wet lightweight aggregates”, Cem. Concr. Res., vol. 31, no. 11, pp. 1587–1591, Nov. 2001.

[55] D. Cusson and T. Hoogeveen, “Internal curing of high-performance concrete with pre-soaked fine lightweight aggregate for prevention of autogenous shrinkage cracking,” Cem. Concr. Res., vol. 38, no. 6, pp. 757–765, Jun. 2008.

[56] B. Akcay and M. A. Tasdemir, “Effects of distribution of lightweight aggregates on internal curing of concrete,” Cem. Concr. Compos., vol. 32, no. 8, pp. 611–616, Sep. 2010.

[57] P. Lura, O. M. Jensen, and S.-I. Igarashi, “Experimental observation of internal water curing of concrete,” Mater. Struct., vol. 40, no. 2, pp. 211–220, Aug. 2006.