



Carbonation behaviour of recycled aggregate concrete



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ABSTRACT

This paper reviews the effect of incorporating recycled aggregates, sourced from construction and demolition waste, on the carbonation behaviour of concrete. It identifies various influencing aspects related to the use of recycled aggregates, such as replacement level, size and origin, as well as the influence of curing conditions, use of chemical admixtures and additions, on carbonation over a long period of time. A statistical analysis on the effect of introducing increasing amounts of recycled aggregates on the carbonation depth and coefficient of accelerated carbonation is presented. This paper also presents the use of existing methodologies to estimate the required accelerated carbonation resistance of a reinforced recycled aggregate concrete exposed to natural carbonation conditions with the use of accelerated carbonation tests. Results show clear increasing carbonation depths with increasing replacement levels when recycled aggregate concrete mixes are made with a similar mix design to that of the control natural aggregate concrete. The relationship between the compressive strength and coefficients of accelerated carbonation is similar between the control concrete and the recycled aggregate concrete mixes.

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1. Introduction

The rapid development of the construction industry and consumption of natural resources and deterioration of the environment in several emerging economies have caused an unsustainable development of the construction industry. For this reason, recycling construction and demolition wastes (CDW) is a vital step in environmental sustainability. However, for this to happen, changes in the management of construction and demolition activities would have to be made in order to implement selective demolition as a replacement for conventional demolition. Selective demolition, also known as deconstruction in some sources, is the systematic disassembly of buildings in order to maximize recovered materials reuse and recycling. While the process of conventional demolition often leads to the mixing of potentially valuable materials and contamination of non-hazardous components, selective demolition allows the use of these separated and uncontaminated materials in future applications.

The concept of selective demolition is still often seen by the construction and demolition industries as being of debateable

economic benefit and little practical value. However, a detailed economic analysis of conventional *versus* selective demolition [1] showed that in spite of the economic viability of selective demolition depending largely on labour costs, tipping fees, and market prices for recovered materials, it may ultimately be more profitable than the conventional demolition approach. Furthermore, there are clear benefits from an environmental point of view from using selective demolition, namely in a direct reduction in the material sent to landfill [2,3] as well as other environmental impacts specifically caused by climatic change, acidification, summer smog, nitrification and amount of heavy metals [4]. These result from the emission of a wide array of substances, all of which are known to be important pollutants.

The use of recycled aggregates (RA), as replacement for natural aggregates (NA), in construction applications has been considered as one of the most effective approaches for recycling given materials from CDW, thus contributing to a greater sustainability in construction. Indeed, extensive scientific research and development work on this subject has been carried out over the last 40 years, which has been becoming increasingly complex, introducing several new variables, in which the durability-related performance has also been considered.

The scope of this investigation was to bring together, analyse and evaluate the published information on the effect of several

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factors related to the use of RA on the carbonation behaviour of concrete. The data, collated from several studies, was subjected to a statistical analysis in order to assess the relationship between carbonation resistance and compressive strength of RAC and also utilized as input information on reinforced concrete degradation models to evaluate RAC suitability as material for reinforced concrete.

2. Recycled aggregates sourced from construction and demolition wastes

According to existing specifications [5–20], there are three main types of RA arising from CDW, which, after being subjected to proper beneficiation processes in certified recycling plants, are suitable for the production of structural concrete; these materials are crushed concrete, crushed masonry, and mixed demolition debris.

Some of these specifications [9,14,15,17] have reached a consensus that, in order to be considered as recycled concrete aggregate (RCA), they must comprise a minimum of 90%, by mass, of Portland cement-based fragments and NA.

RA sourced from crushed masonry, or recycled masonry aggregates (RMA), may include: aerated and lightweight concrete blocks; ceramic bricks; blast-furnace slag bricks and blocks; ceramic roofing tiles and shingles; and sand–lime bricks [21]. RMA are composed of a minimum of 90%, by mass, of the summation of the aforementioned materials.

Aggregates acquired from mixed demolition debris, or mixed recycled aggregates (MRA), are a mixture of the two main components obtained from the beneficiation process of CDW: crushed and graded concrete and masonry rubble. Some specifications [7,15] state that they are composed of less than 90%, by mass, of Portland cement-based fragments and NA. In other words, they may contain several other common CDW materials such as masonry-based materials.

3. Factors affecting the carbonation of recycled aggregate concrete

The durability of concrete is an essential subject as it allows understanding the performance of concrete throughout the service life of a structure. The reduced durability of concrete may be prompted by external agents arising from the environment or by internal agents within concrete [22]. One of the degradation phenomena that deserves most attention is reinforcement corrosion, which is one of the most important and difficult to intervene pathological manifestations that affect reinforced concrete structures [23,24].

The alkalinity resulting from the cement's hydration process protects the reinforcement from corrosion until chemical or physical changes occur, which enable external aggressive agents to act. The two main phenomena that initiate reinforcement corrosion, by destroying the passive coating on reinforcing bars, are carbonation and chloride ingress [25]. Carbonation of concrete can be described as a physical–chemical process in which a series of chemical reactions occur in the presence of carbon dioxide (CO_2), which fosters the reduction of pH in concrete. CO_2 , which penetrates concrete predominantly through a diffusion mechanism, slowly proceeds from the surface of the concrete inwards. The actual rate of carbonation depends on the permeability of concrete, its moisture content and the environment's CO_2 content and relative humidity. In the presence of moisture, CO_2 forms carbonic acid, which reacts with calcium hydroxide ($\text{Ca}(\text{OH})_2$) to produce calcium carbonate (CaCO_3). This process results in a slightly increased strength and

a reduced permeability, as a result of the deposition of CaCO_3 in the voids within the cement matrix [22].

The literature review has shown that recycled aggregate concrete (RAC) tends to exhibit greater carbonation than a corresponding natural aggregate concrete (NAC), and that the magnitude of the difference depends on several factors related to the use of RA that are discussed in the following sections.

3.1. Recycled aggregate replacement ratio

Generally, according to the literature [21,26–42], as the replacement level increases, the carbonation depth of RAC also increases. All other factors remaining constant, since RA have greater water absorption than that of NA, the porosity of RAC is much greater than that of NAC for the same w/c ratio, therefore reducing the carbonation resistance of RAC.

A statistical analysis was performed on the relative carbonation depth of concrete mixes with increasing RA content against that of corresponding NAC mixes. Fig. 1a and b, which include a 95% confidence interval, were based on the results of 600 and 360 measurements from mixes made with coarse and fine RA, respectively, sourced from 10 publications [26,27,30,43–48]. A substantial difference can be seen between the two figures; whilst mixes made with 100% coarse RA content have a 95% probability of exhibiting carbonation depths up to almost 2.5 times greater than that of a corresponding NAC, for the same incorporation ratio of fine RA, this value increased to 8.7 times. This is mainly due to the fact that fine RA normally exhibit greater water absorption than coarse RA and thus increase the permeability of the resulting concrete [36,49,50]. However, by limiting the sample to RCA alone, it was found that when 100% coarse or fine RCA are introduced, the upper limits of the 95% confidence interval suggest that RAC mixes may show carbonation depths up to 2.15 and 6.03 times greater, respectively, than those of the NAC. The value obtained for coarse RCA is practically in agreement with the range proposed by BCSJ [5], which states that RAC produced with coarse RCA may exhibit carbonation depths between 1.2 and 2 times higher than those of controlled mixes.

However, it was perceived that some RAC mixes showed similar or higher resistance to carbonation than NAC, as suggested by the lower limit of the 95% confidence interval in Fig. 1a. This is an unusual occurrence, which may either be due to some coarse RA absorbing part of the mixing water, thus reducing the w/c ratio, or the use of the equivalent mortar volume (EMV) method [46,51]. Xiao et al. [42] also suggested that, since RCA contain old adhered mortar, the total cement content of RAC is greater than that of NAC, which means there are larger quantities of materials available for carbonation, thus improving the carbonation resistance of RAC. This, however, was not noticed for mixes containing fine RA. The lower limit of the 95% confidence range in Fig. 1b shows that the inclusion of increasing amounts of fine RA will most likely cause an increase in carbonation depth.

In some cases [36,52–60], by adjusting the w/c ratio of concrete mixes with increasing coarse RCA in order to obtain the same target strength as that of NAC, it was found that it was possible to obtain specimens with equivalent carbonation depths. Following this line of thought, other researchers [61,62] have also produced RAC with increasing the cement content and replacement levels of RCA and RMA of different sizes. The results showed that the carbonation depths of the resulting RAC with increasing replacement levels of RA of different types and sizes were similar to or lower than those of the NAC.

In another study [63], where RAC mixes exhibited better resistance to carbonation than that of NAC, air dried RCA were used, which may have absorbed part of the mixing water, thereby reducing the w/c ratio. This may have resulted in mixes with less

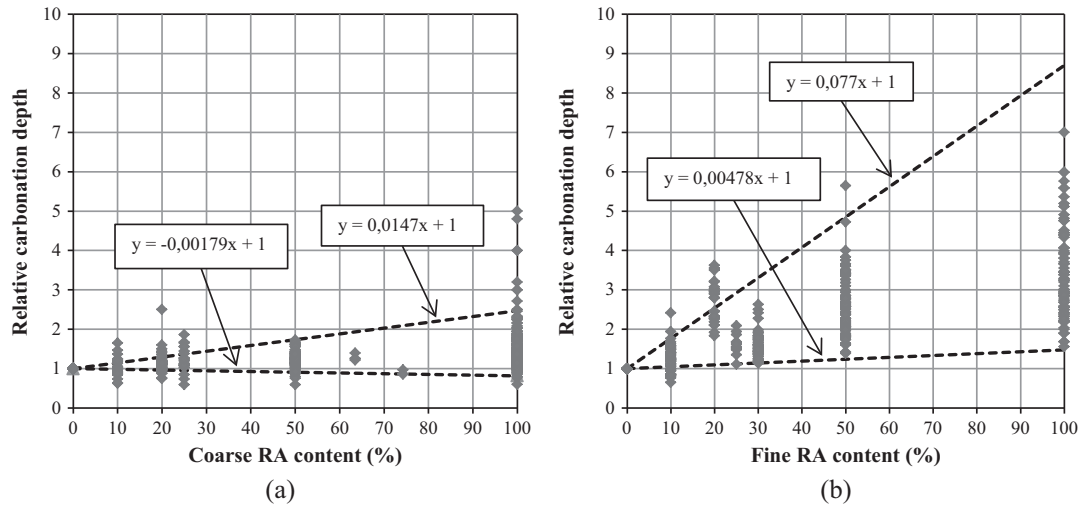


Fig. 1. Relative carbonation depth versus replacement level.

porosity and hence equivalent carbonation depth to that of corresponding NAC mixes.

3.2. Recycled aggregates subjected to different crushing procedures

Pedro et al. [64] studied in depth the influence of the crushing procedure of RA on the properties of RAC. Two types of RCA were studied, one subjected only to a primary crushing stage (RCA-1), whilst the other was subjected to primary plus secondary crushing stages (RCA-2). The second procedure allowed producing rounder RCA with less old mortar adhered to its surface. Concrete mixes made with these aggregates showed strength improvements between 7% and 15% in comparison to mixes made with RCA-1. This trend was also noticeable in the carbonation of concrete. Fig. 2 shows the influence of adding RCA subjected to different crushing procedures on the carbonation of concrete. Results showed that all specimens produced with aggregates subjected to both primary and crushing procedures exhibited slightly lower carbonation depths than when using aggregates subjected to a primary crushing procedure only. This can be explained by two factors. The secondary crushing procedure normally produces aggregates with a more spherical shape, thus allowing better packing of concrete. Since all mixes had to exhibit similar workability levels, the water content had to be reduced, which resulted in reduced porosity. By performing the secondary crushing procedure, there is further reduction of the adhered mortar content, which translates into a less porous aggregate, therefore able to produce concrete with less permeability.

3.3. Quality of the recycled aggregate

Gomes and de Brito [31] performed a very specific and detailed study on the influence of adding different RA types, such as RCA, RMA and MRA, on the durability-related properties of RAC. The MRA used was composed of 30% RMA and 70% RCA. When comparing the carbonation depth of RAC produced with 50% coarse RCA, 25% coarse RMA and 37.5% coarse MRA with that of the corresponding NAC mixes, it was found that they all exhibited around 30% higher carbonation depths. These results are interesting considering that the weighed water absorption and oven-dried density of the aforementioned RA were very similar, which is in agreement with the findings of Silva et al. [65]. In this study, a performance-based classification using the relationship between the water absorption and oven-dried density of RA was proposed. The use of this simple methodology allows categorizing RA based

on their most easily accessible physical properties, instead of classifying them solely based on their composition, as done by some specifications [6,9,14–16,18]. In other studies [66,67], the use of this classification system showed strong and very strong correlations in terms of compressive strength and modulus of elasticity prediction. In other words, as the quality of RA worsens, so does the performance of concrete.

Ryu [39] produced concrete mixes with a w/c ratio of 0.55 and with coarse RCA from materials with different strength and varying adhered cement paste content. All RAC mixes with 100% coarse RCA exhibited 20% greater carbonation depths. With this in mind, the author concluded that the strength of the source concrete and the quantity of adhered mortar had little or no effect on the carbonation depth of RAC when compared to that of the corresponding NAC, provided that the RCA used had similar water absorption. This was also observed in other publications [32,41,68,69].

Katz [44] produced RAC with RCA from concrete materials crushed 1, 3 and 28 days after casting. The reason behind this was to study the effect of subjecting young age concrete materials to a crushing process and understand if it would have any influence on the removal of adhered mortar. Irrespective of crushing age, the results showed that all RCA exhibited similar adhered mortar content and water absorption values, which may have also allowed producing RAC mixes with similar carbonation depths. These findings strengthen the theory behind the aforementioned studies [31,32,39,41,68,69] in that the use of RCA with similar quality allows producing RAC with equivalent behaviour to carbonation, even if the aggregates are subjected to a crushing process at different ages.

Xiao et al. [42] evaluated the influence of adding RA sourced from concrete with different strength on the carbonation of RAC. As expected, the incorporation of 100% coarse RCA resulted in greater carbonation depths. RAC mixes produced with RCA sourced from concrete specimens with compressive strength values of 20 MPa, 30 MPa and 50 MPa exhibited carbonation depths 80%, 26% and 10% greater, respectively, than that of the control NAC.

Cui et al. [70] and Zhang and Yan [71], cited by Xiao et al. [72], have also observed that using RCA from high-strength concrete can reduce the carbonation depth of RAC.

3.4. Exposure to different curing conditions

Since the permeability of concrete is governed by the w/c ratio and the effectiveness of curing, concrete with a high w/c ratio and

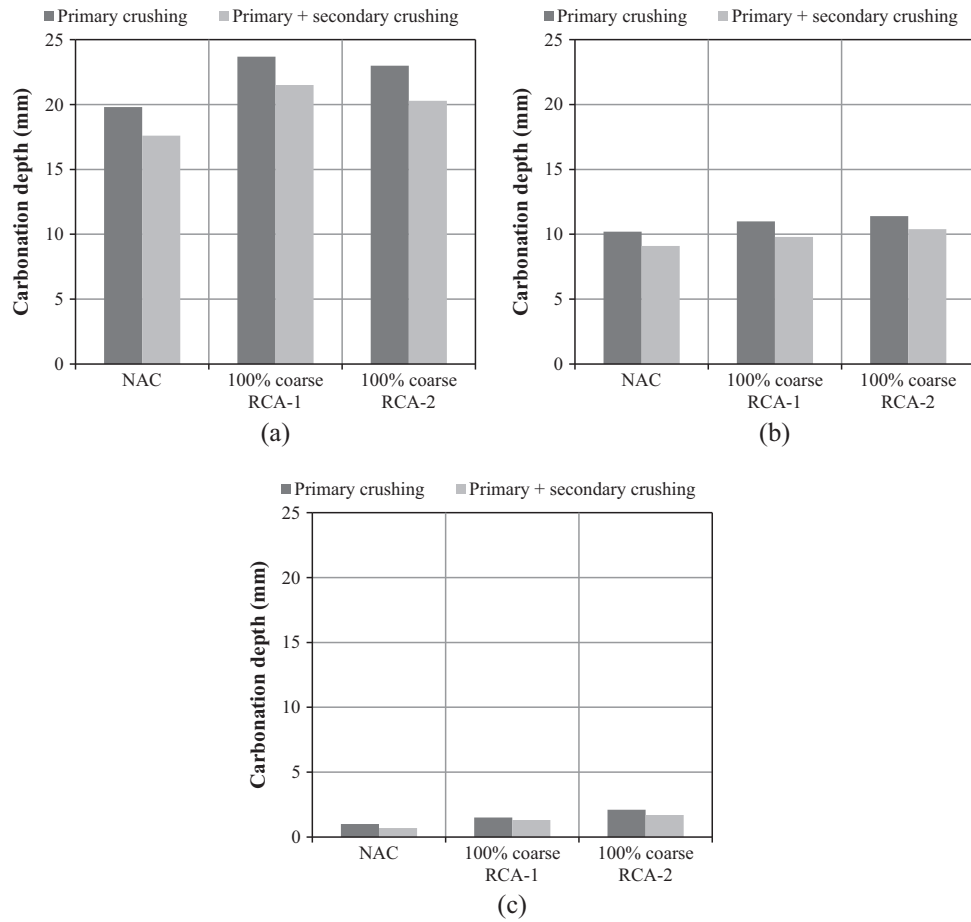


Fig. 2. Carbonation depth of concrete with a target strength of: (a) 20 MPa; (b) 45 MPa; 65 MPa (adapted from Pedro et al. [64]).

inadequately cured will be more prone to carbonation. For concrete made with normal weight aggregates, permeability is mainly governed by the porosity of the cement paste, which is influenced by the *w/c* ratio and age of concrete [22].

The permeability of concrete is generally of the same order when it is made with normal weight aggregates with similar water absorption. However, the use of more porous aggregates will increase the permeability of concrete and thus the carbonation rate [22].

The interruption of moist curing by a period of drying is also known to cause an increase in permeability due to the creation of water passages by minute shrinkage cracks around aggregate particles, especially large ones [22].

Amorim et al. [26] studied the influence of the environmental conditions on the durability-related performance of concrete with increasing coarse RCA content. As the laboratory environment was the driest, with an average relative humidity of 60% and temperature of 20 °C, the specimens cured in it had a greater carbonation depth than those in the other environments considered in the test program (Fig. 3). These specimens showed a clear increase in carbonation depth as the replacement level increased (30% increase when 100% coarse RCA were used, at 91 days).

Other researchers [27] have also performed tests to assess whether exposing RAC to different environmental conditions has any effect on the carbonation depth relative to that of the corresponding NAC mixes. When specimens were cured in a drier environment, the carbonation depths increased proportionally for all mixes.

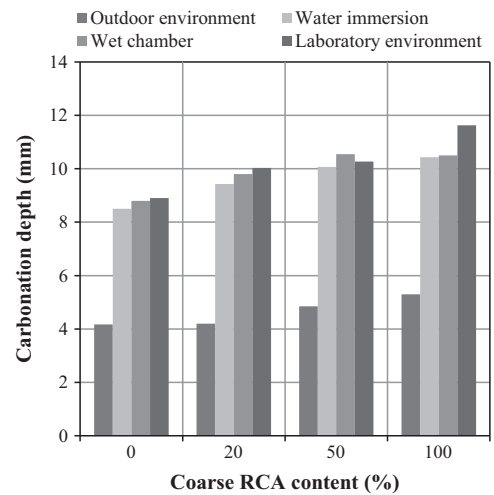


Fig. 3. Carbonated depth of concrete cured in different environments (adapted from Amorim et al. [26]).

3.5. Influence of the water reducing admixtures

Due to the relatively high water absorption and rougher surfaces of RA, a greater amount of water is needed to maintain the same workability of an equivalent NAC composition. By controlling the amount of superplasticizers, it is possible to obtain a concrete

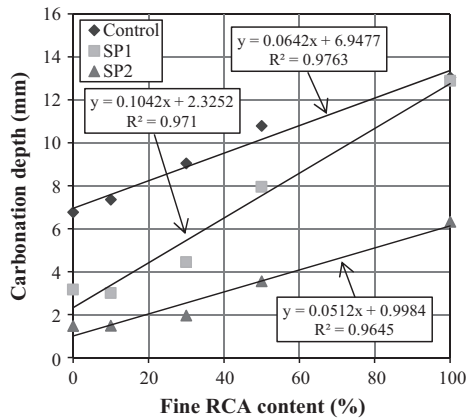


Fig. 4. Influence of superplasticizers on the carbonation depth of concrete made with increasing fine RCA content (adapted from Cartuxo [48]).

mix with the same total w/c ratio as that of the control NAC and offset part of the loss in performance from using RA [73].

An experimental investigation performed by Cartuxo [48] evaluated the carbonation behaviour of concrete produced with increasing fine RCA content and superplasticizers with different water-reducing capacities (Fig. 4). Apart from the control NAC and RAC mixes without any admixtures, two other sets of mixes were made with 1% by weight of cement of water reducing admixtures; one with a regular admixture (SP1) and the other using a high-range water reducing admixture (SP2). Every concrete mix had a fixed cement content of 350 kg/m^3 . As expected, the incorporation of fine RCA resulted in an increase of carbonation depth in all mixes. The results also showed that the use of SP1 allowed producing mixes made with 100% fine RCA with up to 2% less carbonation depth, whilst the use of SP2 decreased carbonation by 52%. These results are a direct consequence of the SP1's lower water reduction efficacy with increasing fine RCA content, since mixes containing this admixture required a greater amount of water for higher replacement levels, which led to greater relative coefficients of accelerated carbonation.

This trend was also observed by Matias et al. [74], who studied the effect of different superplasticizers on the performance of concrete with coarse RCA. It has been suggested that a high internal humidity content alongside the specimens' lower porosity, as a result of a lower w/c ratio, would allow slower water evaporation, similar to an extended cure and thus partially contribute to decrease carbonation depth [27]. The use of superplasticizers delays the cement's hydration time, which is equivalent to a prolonged cure, thus improving the carbonation depth results for mixes using superplasticizers.

3.6. Carbonation over time

Kou and Poon [75,76] studied the long-term mechanical and durability properties of RAC prepared with increasing coarse RCA and varying fly ash content. The carbonation depths of concrete mixes with coarse RCA and exposed to outdoor environment are plotted in Fig. 5. These measurements were taken 28 days, 1, 3, 5 and 10 years after casting (28, 365, 1095, 1825 and 3650 days, respectively). All concrete mixes were produced with a w/c ratio of 0.55 and cement content of 410 kg/m^3 . Over time, the carbonation development of RAC mixes is parallel to that of the corresponding NAC mixes. Furthermore, after 1 year, carbonation seems to be progressing at a linear rate of 0.80–0.85 mm/year, irrespective of the replacement level.

3.7. Effect of mineral additions

Resuming the study conducted by Kou and Poon [75,76], Fig. 5b–d plot the carbonation depth of concrete mixes with varying coarse RCA and fly ash content, measured over the course of 10 years. The results show that incorporating increasing fly ash content led to higher carbonation depths. This is mainly attributed to the lower Ca(OH)_2 content in the concrete containing fly ash, which decreased the amount of constituents capable of becoming carbonated. After 10 years of outdoor exposure, comparison with the concrete mixes without fly ash showed that the NAC and RAC mixes with 100% coarse RCA and with fly ash content of 55% had approximately 70% and 90% greater carbonation depths, respectively.

Sim and Park [77] analysed the carbonation behaviour of concrete mixes made with 100% coarse RCA and incremental ratios of fine RCA as well as varying fly ash content. As expected, as the fly ash content increased so did the carbonation depth of concrete. Again, this can be explained by the concrete's decreasing alkalinity in the cementitious material and the fact that the calcium silicate hydrate (CSH) formed from the pozzolanic reaction absorbs more alkali ions, hence lowering the pH level in concrete [78,79].

In another study [80], however, mixes prepared with RA and fly ash exhibited lower carbonation depths than those of the control NAC. The extrapolated values of the carbonation depth after 1 year were 8.6 mm, 6.5 mm and 5.9 mm, respectively, for control concrete mixes, RAC 27% fly ash by weight of total binder content and RAC without any additions. The reason for this can be easily explained by the mix design; whilst the control mix was produced with a w/c ratio and cement content of 0.56 and 410 kg/m^3 , respectively, for the RAC mix containing fly ash these values were 0.40 and 500 kg/m^3 . This indicates that, besides exhibiting lesser permeability due to being produced with a lower w/c ratio, the latter mix's Ca(OH)_2 content is greater thus leading to slower carbonation rates.

Xiao et al. [42] evaluated the effect of replacing 10% by weight of the cement with fly ash, silica fume and slag on the carbonation behaviour of RAC. The use of these mineral additions resulted in an improvement of the internal pore structure, consequently decreasing the porosity of the RAC, and also improved the ITZ between the coarse RCA and the new cement paste. However, using such materials has also decreased the total alkaline content that can be carbonated, thus resulting in greater carbonation depths (Fig. 6).

In another study, Shayan and Xu [81] added silica fume and lime in a sodium silicate solution. This sodium solution was used to consolidate the RCA's surface in an attempt to improve the interfacial transition zone (ITZ) between the RCA and the new cement paste. However, the use of these materials was not effective since the resulting concrete specimens exhibited greater carbonation depths than mixes with untreated RCA.

4. Relationship between compressive strength and accelerated carbonation coefficient of recycled aggregate concrete

The process of CO_2 diffusion can be modelled after Fick's first law. The initial model to predict carbonation depth [82] is based on the diffusion law and considers that the carbonation rate is proportional to the square root of the time of exposure to CO_2 :

$$x = K\sqrt{t} \quad (1)$$

where x is the carbonation depth (mm); K the carbonation coefficient ($\text{mm year}^{-0.5}$); and t the exposure time to CO_2 (year).

The carbonation coefficient summarises several parameters, assumed to be constant: CO_2 concentration, the amount of CO_2

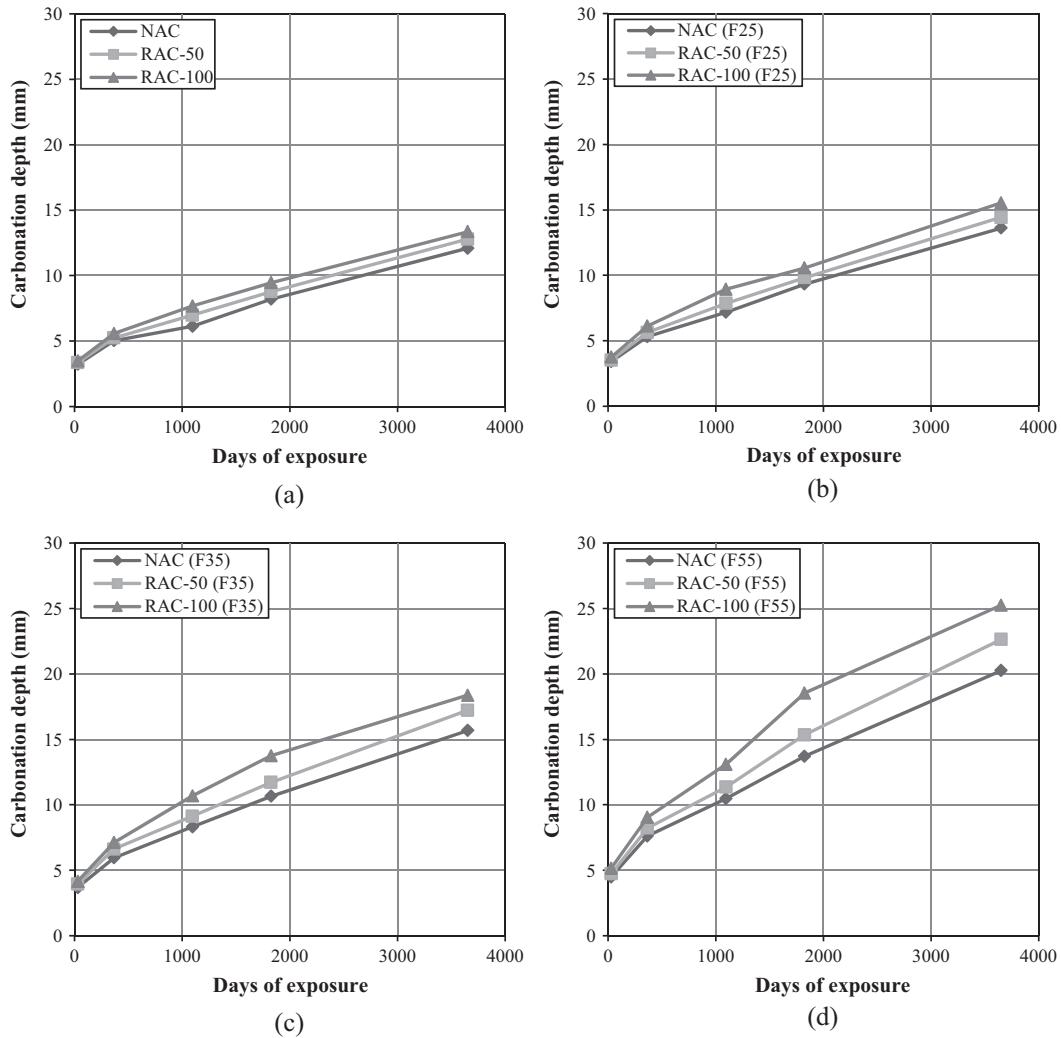


Fig. 5. Carbonation depth over time of concrete mixes with increasing coarse RCA content and varying fly ash content: (a) No fly ash; (b) 25% fly ash; (c) 35% fly ash; 55% fly ash (adapted from Kou and Poon [75,76]).

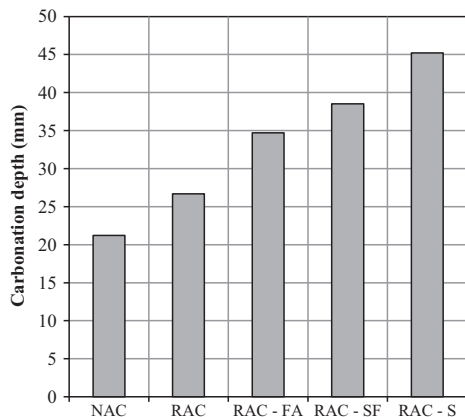


Fig. 6. Effect of mineral additions on carbonation depth of RAC (FA – fly ash; SF – silica fume; S – slag) (adapted from Xiao et al. [42]).

required to carbonate a unit volume of concrete, and diffusion coefficient for CO₂ through carbonated concrete.

However, in real exposure conditions, CO₂ concentration is not constant over time, the diffusion coefficient is sensitive to relative humidity and dry-wet cycles and the amount of CO₂ required to

carbonate a unit volume of concrete depends on the amount of CO₂ available inside it [83], because for regular CO₂ concentrations only the hydrated cement compounds react with CO₂, while for high CO₂ concentrations these and the anhydrous cement compounds both react with it [84].

The use of concrete's compressive strength to estimate the resistance to carbonation is frequent. There have been proposals for linear [85], exponential [86] and power equation relationships [87] between these two properties.

Fig. 7 presents the relationship between the coefficient of accelerated carbonation (k_{ac}) and the 28-day compressive strength of mixes with varying coarse and fine RA content. Fig. 7a and b are based on the results of 630 and 479 measurements, respectively, sourced from several publications [26,27,30,43–48]. Concrete mixes used in this figure were exposed to a controlled environment containing 4–5% CO₂ content and contain several RA types (i.e. RCA, RMA, MRA). By analysing the power regressions belonging to NAC and RAC mixes with 100% coarse RA, presented in Fig. 7a, it is seen that their development is very similar. This trend can also be seen in Fig. 7b, where the regressions obtained for mixes with varying fine RA content show negligible differences. These results suggest that the coefficient of accelerated carbonation mainly depends on the compressive strength of concrete regardless of the content, type and size of RA. In other words, for

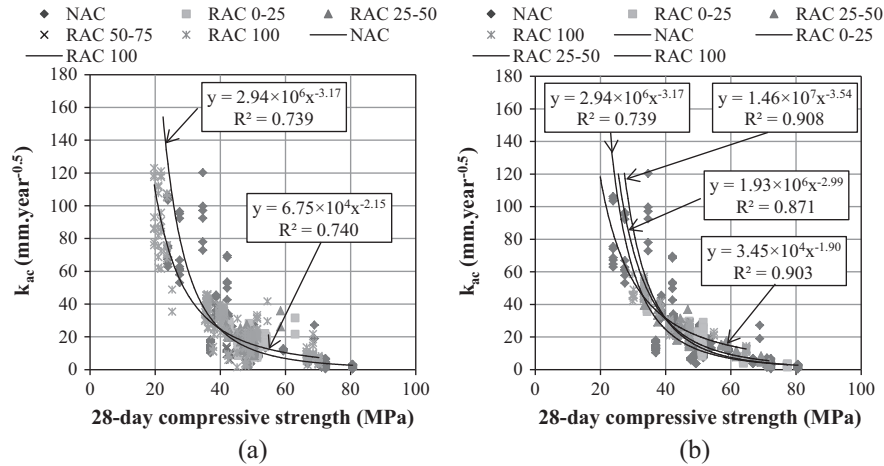


Fig. 7. Relationship between the coefficient of accelerated carbonation and the 28-day compressive strength for mixes with varying: (a) coarse RA content; (b) fine RA content.

the same compressive strength, RAC mixes will present similar carbonation coefficient to those of NAC mixes. This is in agreement with several researches [36,52–60], in which the authors adjusted the *w/c* ratio of RAC mixes in order to obtain similar compressive strength to that of the control NAC.

However, the statistical analysis performed in Section 3.1 showed that RAC mixes with increasing RA content tend to exhibit greater carbonation depths, and thus coefficients of accelerated carbonation, than those of the NAC produced with a similar mix design (i.e. cement content, effective *w/c* ratio). Generally, for the same mix design, RAC mixes exhibit decreasing compressive strength with increasing RA content. This was established in a statistical analysis, performed by the authors in their previous study [66], based on the results of 787 concrete mixes, made with coarse and fine RA of different type and origin, sourced from 65 publications. For this reason, it is reasonable to assume that the increase of the coefficient of accelerated carbonation is inversely proportional to the compressive strength with increasing RA content, which explains the similar correlation between these two properties in RAC and NAC mixes. Using the upper limits of the 95% confidence interval expressed in Fig. 1, it was possible to obtain a set of correction factors for the coefficient of accelerated carbonation of concrete mixes with increasing coarse or fine RCA content (see Table 1). These may only be applied in RAC mixes with a similar mix design to that of reference NAC.

Considering the previous results, and given the positive experience in other studies [88–90] of power type regression functions to estimate the coefficient of accelerated carbonation, based on the compressive strength, the authors decided to use a power regression for all concrete mixes regardless of RA type, size and content (see Table 1). A coefficient of determination (R^2) of 0.74 was obtained, which means that 74% of the total variation of the coefficient of accelerated carbonation can be explained by its relationship with the 28-day compressive strength. The remainder may be explained due to a number of factors, which depend on each experimental investigation. These include compaction and curing

conditions of concrete, type of cement, cement amount, *w/c* ratio, conditions of exposure to CO₂ and even the porosity of the RA themselves. According to Piaw [91], the corresponding coefficient of correlation ($R = 0.86$) shows that there is a strong correlation between the two variables. The number and variability of data used, makes this result more relevant. Actually, when applying the correlation test [92] to assess whether the correlation coefficient is statistically significant, a *p*-value of 2.85×10^{-277} was obtained.

The *p*-value represents the level of confidence to accept the null hypothesis. In this test, the null hypothesis is that the two variables are not correlated, while the alternative hypothesis is that they are. In this test, the *p*-value is the probability returned by a Student distribution, with $N - 2$ degrees of freedom, for the test statistic calculated as:

$$T = R \sqrt{\frac{N - 2}{1 - R^2}} \quad (2)$$

where T is the statistic of correlation test, R is the correlation coefficient ($R = 0.86$) and N is the number of measurement pairs ($N = 933$). As the null hypothesis cannot be accepted for reasonable levels of confidence, the variables are assumed to have a statistically significant correlation.

The upper and lower limits of the 95% confidence interval can also be seen in Fig. 8. As observed in another study [90], the dispersion of the coefficient of accelerated carbonation tends to be higher in concrete mixes with lower compressive strength. The upper and lower limits of the confidence interval are, respectively:

$$k_{ac} = 1.20 \times 10^6 f_{cm}^{-2.696} \quad (3)$$

$$k_{ac} = 1.70 \times 10^5 f_{cm}^{-2.698} \quad (4)$$

Fig. 9 presents a comparison of the curves shown in Fig. 8 with those obtained in other publications [87,90]. For the same compressive strength, the relationship proposed by Neves [90] returns a greater coefficient of accelerated carbonation than that of the regression obtained in this paper. The relationships proposed by Gonçalves et al. [87] for mixes produced with other types of cement) result in a higher coefficient of accelerated carbonation for compressive strength values over 25–35 MPa. Nevertheless, all curves were similar to or below the upper limit of the 95% confidence interval, except for the LNEC-E465b curve. This may be due to the fact that this curve corresponds to concrete mixes made with cement types other than type CEM I cement, which is

Table 1
Correction factors for coefficient of carbonation for mixes with increasing RCA.

Coefficient of carbonation correction factors					
20% RCA		50% RCA		100% RCA	
Coarse	Fine	Coarse	Fine	Coarse	Fine
1.25	2.00	1.60	3.50	2.15	6.00

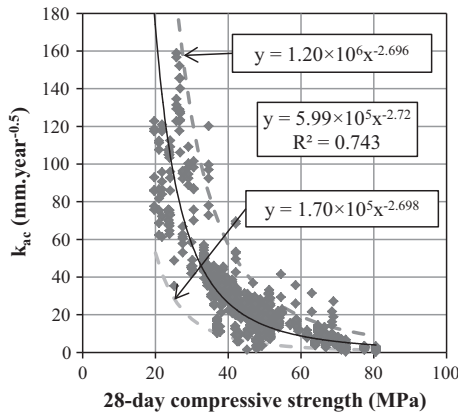


Fig. 8. Relationship between the coefficient of accelerated carbonation and the 28-day compressive strength for all mixes.

normally used by researchers to produce RAC. In fact, most of the values that were above the upper limit belong to Kou and Poon [75], who produced RAC mixes using a binder with increasing fly ash content as partial replacement for cement. For this reason, they obtained higher coefficients of accelerated carbonation, for the same compressive strength, in comparison to those of other concrete mixes produced with cement type CEM I [94].

5. Carbonation induced corrosion of reinforced recycled aggregate concrete

Reinforcing steel corrosion is the most common deterioration mechanism in reinforced concrete structures [95–97] and is usually induced by concrete carbonation or chloride penetration. Although chloride-induced corrosion is considered to be worse than carbonation-induced corrosion, Parrott [98] apud Jones et al. [99] states that 2/3 of all structural concrete is exposed to environmental conditions that favour carbonation-induced corrosion. In Taipei, significant carbonation-induced corrosion of existing concrete bridges has been observed before 10–15 years after construction [100]. Therefore, concrete resistance to carbonation is paramount information. To evaluate carbonation resistance, usually expressed as a carbonation coefficient (see Eq. (1)), with timely delivery of results, accelerated tests have to be used in which concrete is exposed to mediums with relatively high CO₂.

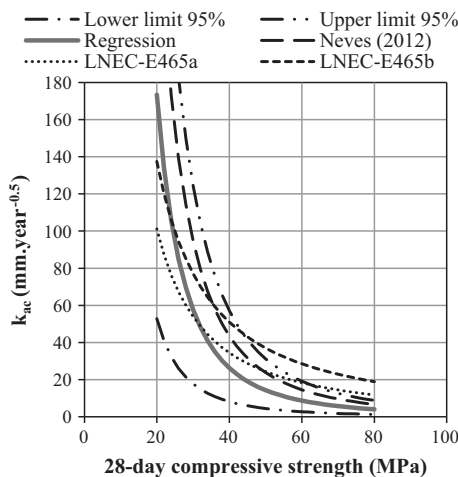


Fig. 9. Comparison of relationships between the coefficient of accelerated carbonation and the 28-day compressive strength.

There have been attempts to establish a linear relationship between the coefficients of accelerated carbonation and those of natural carbonation of concrete [84,101,102]. This would allow predicting the carbonation depth of concrete subjected to natural conditions by means of simple and relatively fast laboratory tests. Indeed, some specifications already consider linear relationships in carbonation models [93,103].

Neves et al. [102] investigated the linear relationship between the carbonation resistance in accelerated and natural conditions, using cores drilled from 96 locations in real structures, using different structural elements, exposed to environmental class XC3 or XC4 [104], whose age ranged from 4 to 32 years. This investigation allowed the authors predicting the carbonation depth evolution over time in natural conditions by using the following model:

$$x = \frac{k_{ac}}{k_e} \sqrt{t} \tag{5}$$

where x is the carbonation depth (mm); k_{ac} the coefficient of accelerated carbonation (mm year^{-0.5}); k_e the environmental parameter, being 9.9 for environmental class XC3 and 15.0 for environmental class XC4; and t is the exposure time to CO₂ (year).

A description of the environment of XC3 and XC4 classes can be found in EN 206-1 [104].

Based on Eq. (5) and on reliability concepts, Neves et al. [23] proposed a methodology to establish requirements regarding resistance to carbonation induced corrosion of reinforced concrete, by using the following formula:

$$k_{ac} = \frac{c_d \cdot k_e}{\gamma_s \cdot \sqrt{t_{sl}}} \tag{6}$$

where k_{ac} is the coefficient of accelerated carbonation (mm year^{-0.5}); c_d the reinforcement cover design value (mm); k_e the environmental parameter; γ_s is the safety factor, being 1.0 for environmental class XC3 and 1.25 for environmental class XC4; and t_{sl} is the specified service life (year). This methodology is a variation of the approach proposed in the Model Code for Service Life Design (MCSLD) [103].

Assuming the validity of the aforementioned methodologies for RAC, with the use of accelerated carbonation tests, it is possible to estimate the required accelerated carbonation resistance of a reinforced RAC exposed to natural carbonation conditions.

Considering both methodologies and the most severe environmental classes (XC3 and XC4), as well as the reinforcement covers specified in Table 4.4N of EN 1992 [105] for a structural class S4 and a intended service life of 50 years, the threshold values of accelerated carbonation coefficients, which represent the inverse of accelerated carbonation resistance, are presented in Table 2. Although it may seem odd to have less demanding accelerated carbonation resistance requirements for the most aggressive of the environmental classes considered, one should bear in mind that design reinforcement cover is different in the two classes, being thicker (more protective) for XC4, thus allowing less demanding accelerated carbonation resistance.

A cumulative distribution of accelerated carbonation coefficients of mixes containing RA, collected in literature, is presented in Fig. 10, where the threshold values presented in Table 2 are also

Table 2
Maximum allowable accelerated carbonation resistances.

Environmental class	Accelerated carbonation coefficient (mm/year ^{0.5})	
	Neves et al. [23]	MCSLD [103]
XC3	35	24
XC4	50	47

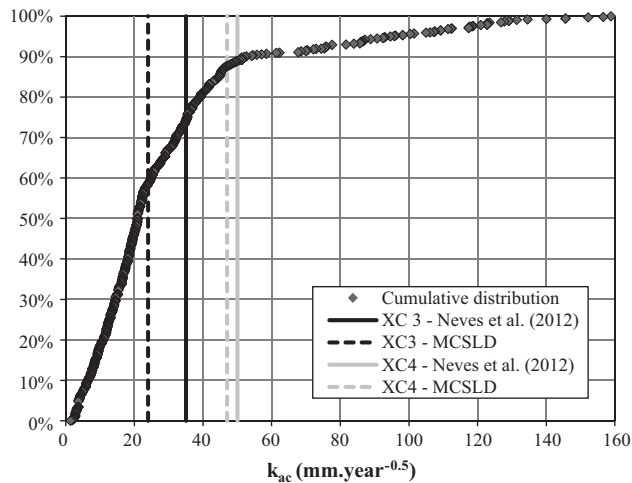


Fig. 10. Cumulative distribution of RAC accelerated carbonation coefficients.

identified. Approximately 88% of the collated RAC mixes are fit for XC4 environmental class, considering a target service life of 50 year and a nominal reinforcement cover of 35 mm, while for XC3 environmental class with a nominal reinforcement cover of 40 mm, the ratio drops to 74%, considering the methodology proposed by Neves et al. [23] or 59%, considering the methodology from MCSLD [103]. Therefore, one can infer that it is not difficult to design RAC mixes fit for reinforced concrete structures.

Nevertheless, as some of the collated RAC mixes do not fulfil the required accelerated carbonation resistance, a deeper analysis was made aiming at finding the parameters that can limit the use of RAC in reinforced concrete. It turned out that neither the source nor the size and percentage of replacement of RA prevent *per se* the application of RAC in reinforced concrete subject to environmental classes XC3 and XC4. Therefore, the analysis continued comparing the limiting values for composition and properties of conventional concrete mixes, recommended in EN 206-1 [104], with those of collated RAC mixes fulfilling the required accelerated carbonation resistance (Table 2). It was found that, except in one study, all RAC mixes that meet the recommended limits for conventional concrete mixes are suitable for reinforced concrete, subject to XC3 and XC4 environmental classes. The exception is a case in which a considerable percentage of replacement of cement by fly ash (over 20%) was used [75], where the accelerated carbonation resistance did not fulfil the requirements for the more demanding environmental class (XC3), in terms of accelerated carbonation resistance. As the limiting values for composition and properties of conventional concrete mixes, recommended in EN 206-1 [104], are applicable when binder is CEM I [94], the reported exception must be devalued. Therefore, this analysis makes it very clear that RAC is a suitable material for reinforced concrete structures subject to carbonation induced corrosion, since the RAC mixes meet the recommended limiting values in EN 206-1 [104] for composition and properties of conventional concrete mixes.

6. Conclusions

The following conclusions were drawn from studying the various factors related to the inclusion of RA on the carbonation of concrete:

- The incorporation of increasing amounts of RA causes greater carbonation depths, assuming all other factors are equal. The use of 100% coarse RCA in concrete may cause up to 2 times the carbonation depths of those of the corresponding NAC mixes;

- As far as the RA type effect on carbonation is concerned, it was found that, for a given replacement level, RMA cause greater carbonation depths than RCA. In an MRA blend, as the RMA content increases so does the carbonation depth of the resulting concrete. Since carbonation is closely related to the porosity of concrete, it is obvious that the incorporation of increasingly porous RA will create a more permeable concrete, and hence greater carbonation depths;
- The size of the RA also has a clear effect on the carbonation behaviour of concrete. There is a greater probability that concrete mixes made with fine RCA exhibit greater carbonation depths than those of mixes with coarse RCA. This can be easily explained by the greater porosity of the fine RCA due to the greater amount of adhered mortar, which could not be separated during the recycling process;
- The incorporation of extra crushing stages during the RCA's recycling process may result in lower carbonation depths. This happens as a result of the aggregates' rounder surface, which allows better packing, and also because of the lower content of porous adhered mortar;
- The strength of the original material has little or no effect on the carbonation depth of concrete provided that RA obtained from them exhibit similar water absorption. Nevertheless, it is also possible that the RCA sourced from concrete materials with different target strength also exhibit different water absorption values. In these cases, there is a clear difference in the internal porosity of the RCA's adhered mortar, which will affect the permeability of the resulting concrete and hence its response to carbonation;
- The incorporation of coarse RCA from concrete materials crushed at different ages had no effect on the carbonation depth of concrete, i.e. regardless of the age at which a concrete material is processed, the resulting RCA will produce concrete with similar resistance to carbonation;
- When compared to a corresponding NAC, RAC specimens with a given replacement level appear to exhibit a similar difference in carbonation depth regardless of the curing conditions. This means that the environmental conditions in which the concrete specimens are cured have no effect on the carbonation depth of RAC mixes with increasing RA content relative to NAC under the same curing conditions;
- It is possible to produce RAC with similar target strength and carbonation depths to those of a conventional concrete. However, for this to happen, a greater amount of cement would have to be used in the RAC's production to compensate the RA's greater porosity in relation to that of the NA. Another approach would be decreasing the w/c ratio whilst maintaining the cement content. Naturally, this mix would have to be accompanied by superplasticizers in order to maintain similar workability levels;
- Reducing the w/c ratio of RAC mixes with the help of water reducing admixtures is an effective method to increase mechanical performance as well as to reduce carbonation. However, it was also concluded that it is preferable to control the quality and content of RA in the mix, since these have a greater influence on this property than lowering the w/c ratio by using water reducing admixtures;
- Concrete specimens with increasing replacement levels and exposed to an outdoor environment showed slightly higher coefficients of carbonation, yet with a parallel carbonation development over a period of 10 years. In other words, the absolute difference in carbonation depth between a RAC and a corresponding NAC appears to remain unchanged over time;
- The use of mineral additions as cement replacement causes greater carbonation depths than those of mixes without them. This happens because the $\text{Ca}(\text{OH})_2$ content decreases thus

lowering the pH of concrete. Nevertheless, irrespective of the presence of RCA, the difference in carbonation depth is similar over time to that of the corresponding NAC, with or without any mineral additions;

- RAC mixes exhibit a similar relationship between the coefficient of accelerated carbonation and compressive strength when compared with NAC. The relationship presented in this study, which was compatible with those obtained in other publications, is applicable to concrete mixes produced with cement type CEM I;
- The use of the relationships and methodologies presented in this paper showed that RAC mixes meeting the recommended limiting values for conventional concrete mixes exhibit carbonation resistance performances adequate to accomplish the target service life and therefore that RAC is a suitable material for reinforced concrete structures subject to carbonation induced corrosion. This may facilitate the wider use of RA in the production of structural concrete, since it shows compatibility with conventional NAC and it is reasonably easy to design for a given environmental class, target service life and reinforcement cover.

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