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# Prediction of Chloride Ion Penetration of Recycled Aggregate Concrete

***Rui Vasco Silva[a], Jorge de Brito[b]*, Rui Neves[c], Ravindra Dhir[d,e]***

[a]*Civil Engineering Research and Innovation for Sustainability - CEris, Instituto de Engenharia de Estruturas, Território e Construção – ICIST, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisbon, Portugal*
[b]*Civil Engineering Research and Innovation for Sustainability - CEris, Departmento de Engenharia Civil, Arquitectura e Georrecursos - DECivil, Instituto de Engenharia de Estruturas, Território e Construção – ICIST, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisbon, Portugal*
[c]*Escola Superior de Tecnologia do Barreiro, Instituto Politécnico de Setúbal, R. Américo da Silva Marinho, 2939-001, Barreiro, Portugal*
[d]*School of Civil Engineering, University of Birmingham, B15 2TT, Birmingham, United Kingdom*
[e]*Applying Concrete Knowledge, 1A Blakeney Avenue, Birmingham, B17 8AP, United Kingdom*

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This paper provides a literature review and analysis of the various influencing aspects related to the use of recycled aggregates, sourced from construction and demolition waste, on the chloride ion penetration of concrete. A statistical analysis on the effect of incorporating increasing amounts of recycled aggregates of different type, size, and class on the chloride ion migration and total charge passed of concrete is also presented. The paper also presents the relationship between these properties and the corresponding compressive strength. The results show strong correlations between these parameters, which are independent of other aspects related to recycled aggregate use and made it possible obtaining a relationship between the values acquired *via* NT Build 492 and ASTM C1202.

**Keywords:** *recycled aggregates, construction and demolition waste, chloride ion penetration, concrete*

## 1. Introduction

The expansion of the world's population has led to an exponential increase in the consumption of natural resources and energy, consequently leading to increasing amounts of waste. Therefore, recycling construction and demolition waste (CDW) is a vital step towards environmental sustainability in the construction industry.

Changes in the management of construction and demolition activities will have to be made in order to implement selective demolition as opposed to conventional demolition. The concept of selective demolition is still often seen by the industry as having 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 conventional demolition. Furthermore, there are clear benefits from an environmental point of view from using selective demolition, namely a direct reduction of 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].

The use of recycled aggregates (RA), as replacement for natural aggregates (NA), in construction applications has been considered one of the most effective approaches for recycling specific materials from CDW, thus contributing to a greater sustainability in construction.

The aim of this investigation was to analyse the various influencing aspects related to the use of RA, sourced from construction and demolition waste, on the chloride ion penetration of concrete. With the purpose of understanding the effect of introducing an increasing amount of RA on the resistance to chloride ion penetration, a statistical analysis was also performed on data gathered from several studies. It was also the authors' objective to produce a generic prediction model that yields concrete's chloride migration coefficient and total charge passed as a function of the corresponding compressive strength.

## 2. Recycled Aggregates Sourced from Construction and Demolition Waste

According to existing specifications[5-20], there are three main types of RA resulting 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

*e-mail: jb@civil.ist.utl.pt

aggregate (RCA), a given aggregate must comprise a minimum of 90%, by mass, of Portland cement-based paste 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 Chloride Ion Penetration 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 deserve most attention is reinforcement corrosion, which is one of the pathological manifestations most important and difficult to intervene 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 its passive coating are carbonation and chloride ingress[25].

The strongly alkaline nature of calcium hydroxide ($Ca(OH)_2$) prevents the corrosion of steel reinforcements by the formation of a thin protective film of iron oxide on their surface. However, if water and oxygen are present, there may come a time when carbonation or soluble chlorides reach the steel and then corrosion of reinforcement may take place. The deleterious action of chloride ions may come from internal agents, such as aggregates with high chloride content or from calcium chloride used as an accelerator when concrete is placed at very low temperatures or even from mixing water. Chlorides may also come from external sources, e.g. de-icing salts, pools and marine environment[22].

Corrosion of steel occurs because of electrochemical action, which usually occurs when two dissimilar metals are in electrical contact in the presence of moisture and oxygen. Chloride ions surrounding the reinforcement react at anodic sites to form hydrochloric acid, which destroys the passive layer. The steel's surface then becomes activated locally to form the anode, with the passive surface forming the cathode. The ensuing corrosion is in the form of localized pitting[22].

According to EN 206[26], the maximum chloride content allowed is 1.0% by mass of cement for concrete not containing any embedded steel except for corrosion-resisting lifting devices (Table 1). For steel reinforcement or other embedded metal, two limits are given: 0.2% and 0.4%. Similarly, for prestressed concrete, two limits, lower than the previous ones, are given: 0.1% and 0.2%.

EN 197[27] specifies a limit of 0.1% of chloride content in cement. In cases where the cement is type CEM III, it may contain more than 0.1%, but the value must be declared. For prestressed concrete, cements may be produced with a lower value, which will replace the aforementioned and must be reported by the manufacturer.

EN 12620[28] states that aggregates may contain chlorides in the form of salts, the limit amount of which mainly depends on the aggregates' origin. To minimize the risk of corrosion of embedded metals, it is normal to limit the total amount of chloride ions for all constituents of concrete. Following standard EN 1744-1: "Tests for chemical properties of aggregates - Part 1: Chemical analysis"[29], it is possible to determine the chloride content, which if lower than 0.01% then this value may be used in the calculation of the total chloride ion content of all constituents.

A study[30] on the comparison of several specifications for the use of RA in concrete shows that the maximum allowed chloride content is, in most cases[9,11,16,18], between 0.03% and 0.15%. NBR-15.116[15] has a less demanding limit for chloride content (1%) of water soluble chlorides. It is normal to find RA with higher levels of chloride than those of NA[31] because they may either contain old adhered mortar with relatively high chloride content, or the original material may have been in contact with a chloride-enriched environment[10,32]. Nevertheless, chlorides contaminating the RA may leach if they are soaked in water. Washing with water is one way of reducing the concentration of these constituents because they are not bonded to the cementitious microstructure and

**Table 1.** Maximum chloride content of concrete according to EN 206[26].

| Concrete use | Chloride content class[a] | Maximum $Cl^-$ content by mass of cement[b] |
|---|---|---|
| Not containing any steel reinforcement or other embedded metal with the exception of corrosion-resisting lifting devices | Cl 1.0 | 1.0% |
| Containing steel reinforcement or other embedded metal | Cl 0.2 | 0.2% |
| | Cl 0.4 | 0.4% |
| Containing prestressing steel reinforcement | Cl 0.1 | 0.1% |
| | Cl 0.2 | 0.2% |

a - For a specific concrete use, the class to be applied depends upon the provisions valid in the environment where concrete is used. b - Where type II additions are used and are taken into account for the cement content, the chloride content is expressed as the percentage of chloride ions by mass of cement plus total mass of additions that are taken into account.

are thus easy to remove from RA. Debieb et al.[33] suggested that, after a thorough washing or total immersion in water for at least 2 weeks, the chlorides content decreases to a point where these RA can be used in reinforced concrete and even in prestressed concrete. However, this procedure has environmental impacts that need to be quantified.

The literature review has shown that recycled aggregate concrete (RAC) tends to exhibit greater chloride ion penetration 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. It was also observed that the chloride ion penetration in RAC is evaluated, in most cases, using one of two methods. The most widely used one is that of ASTM C1202: "Standard test method for electrical indication of concrete's ability to resist chloride ion penetration"[34]. This test does not directly measure the depth or rate of chloride ions penetration, but rather the electrical conductance of concrete, which can be correlated with chloride ion penetration. This is a problem since it makes it difficult to directly correlate results from the test with a target service life and has led to a significant amount of debate about the proper use and applicability of the test[35,36]. In quality control and acceptance testing applications, the ASTM C-1202 recommends the use of the qualitative terms shown in Table 2, rather than the numerical results of the test[34,37].

The other method is the Nordtest Method NT Build 492: "Concrete, mortar and cement-based repair materials: Chloride migration coefficient from non-steady-state migration experiments"[38]. This test method assesses the coefficient of chloride migration, which is a measure of the resistance of the tested material to chloride penetration. This non-steady-state migration coefficient cannot be directly compared with chloride diffusion coefficients obtained from other test methods, such as the non-steady-state immersion test or the steady-state migration test.

## *3.1. Recycled aggregate replacement level*

There is a consensus in the literature review that, as the replacement level increases, so does the chloride ion penetration[39-61]. This is justified by the permeable nature of RA, which is known to decrease resistance to chloride ion penetration[62].

**Table 2.** Chloride permeability based on total charge passed[34,37].

| Total charge passed (Coulombs) | Chloride permeability | Typical of |
|---|---|---|
| > 4000 | High | High w/c ratio (> 0.60) conventional Portland cement concrete (PCC) |
| 2000 - 4000 | Moderate | Moderate w/c ratio (0.40-0.50) conventional PCC |
| 1000 - 2000 | Low | Low w/c ratio (< 0.40) conventional PCC |
| 100 - 1000 | Very low | Latex-modified or internally-sealed concrete |
| < 100 | Negligible | Polymer-impregnated concrete, polymer concrete |

Although more costly and against the notion of a more sustainable concrete, adjusting the w/c ratio, by increasing the cement content, is an effective way of producing RAC mixes with the same target strength as that of conventional concrete mixes. Researchers[63-71] found that it is possible to produce RAC mixes with 100% coarse RCA with equivalent or even greater resistance to chloride ion penetration when compared to NAC.

Figure 1 presents the relative effect of introducing increasing amounts of coarse or fine RA on the chloride migration coefficient and total charge passed. This figure was based on 1115 measurements, taken from mixes with increasing amounts of RA of different size, type and quality, sourced from 31 publications[39,40,44,47,50-52,54,55,57,59-61,72-89]. Figure 1a and b suggest that increasing amounts of fine RA cause a greater increase in the chloride migration coefficient than when using coarse RA. This was to be expected, considering the higher permeability of fine RA in comparison to that of coarse RA[90]. The 95% upper confidence limit (95% UCL) in Figure 1a and b suggests that, when using 100% coarse or fine RA, there is a probability of 95% that the chloride migration coefficient may increase up to 1.65 and 2.95 times, respectively. Nevertheless, since there is a propagation of error at higher replacement levels because of greater than expected migration in low replacement levels, it is more likely that mixes with 100% fine RA exhibit coefficients of migration 2.30 times that of NAC.

Although the 95% lower confidence limit (95% LCL) in Figure 1b suggests that the use of fine RA may significantly increase resistance to chloride ion penetration, further analysis of the results showed that this only happened when using fine RMA. In this experimental investigation, the authors[89] studied the durability-related performance of concrete containing fine RMA from crushed bricks. Since clay bricks normally contain high contents of alumina ($Al_2O_3$)[91], which are comparable to those of metakaolin and fly ash[92], it is possible that by grinding them to a fine enough state they may cause a pozzolanic reaction with the cement, producing tricalcium aluminate ($3CaO.Al_2O_3$ or $C_3A$) which is known to be partly responsible for the chemical binding of chloride ions to form Friedel's salt ($Ca_6Al_2O_6.CaCl_2.10H_2O$).

Figure 1c presents the relative effect of adding increasing amounts of coarse RA to the total charge passed. Although some RAC exhibited lower charge passed than that of the control concrete, the 95% confidence limits suggest that there is a probability of 95% that the total charge passed of concrete made with 100% coarse RA will either maintain or increase up to 2 times that of the control NAC.

Very few authors[80,87,93] have reported similar or even higher resistance to chloride ion penetration with increasing RA content. While some[93] did not explain this phenomenon, others[80,87] showed a common ground. These researchers, who produced RAC mixes made with 100% coarse RCA and increasing fine RCA content, also introduced fly ash in varying amounts. In most mixes, as the fine RCA content increased, so did the resistance to chloride ion penetration. Mixes with 100% fine RCA exhibited reductions of 400 to 850 Coulombs passed. This effect was explained by the filler effect of the fine RCA as it comprised a higher percentage of small particles than the fine NA.

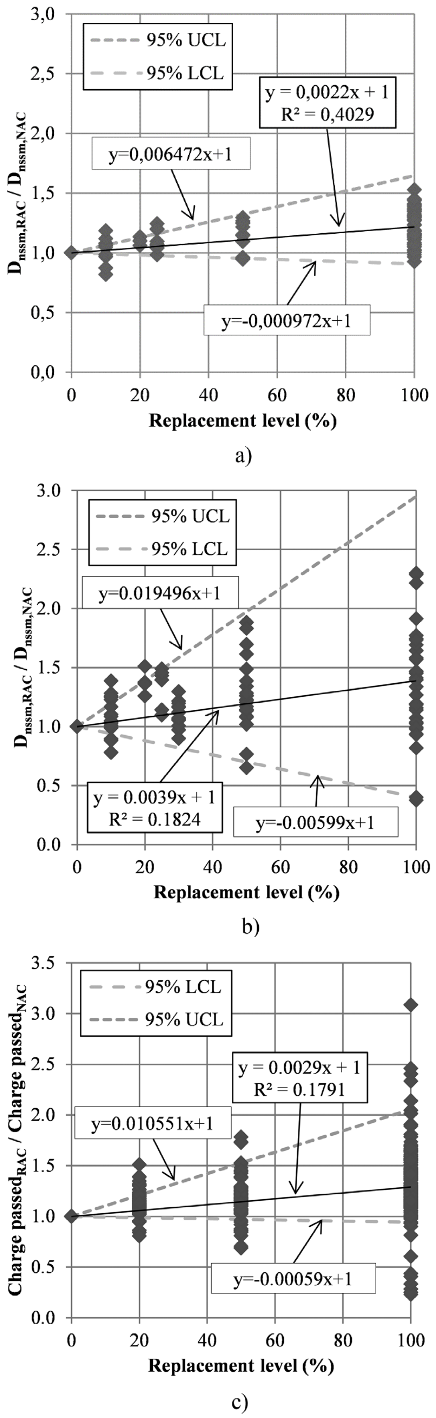


**Figure 1.** Influence of increasing coarse (a) and fine (b) RA on the chloride migration and coarse (c) RA on the total charge passed.

## 3.2. *Quality of the recycled aggregate*

It is important to understand the concept of the quality of RA since it can be affected by a number of factors and is also known to have a significant influence on the performance of the resulting concrete. The quality of RA is influenced according to their size, type and beneficiation procedures used[90].

As stated in section 3.1, concrete with fine RCA is more susceptible to chloride ion penetrability, mainly because of the fine RCA's greater adhered mortar content and thus increased permeability[90,94]. However, as mentioned in the previous section, the use of fine RMA may actually decrease diffusivity because of the high alumina contents[89,95,96].

Gomes & Brito[41] studied the influence of adding different RA types, i.e. RCA, RMA and MRA, to the durability-related properties of RAC. The MRA used was composed of 30% RMA and 70% RCA. The results showed that, when using 50% coarse RCA, 37.5% coarse MRA and 25% coarse RMA, the chloride ion migration coefficients increased by 5.6%, 15.1% and 18.8%, respectively. This suggests that, because of the RMA's greater porosity, the resulting concrete may exhibit higher chloride ion penetration depths. This was also reported by Paine & Dhir[97], who observed that, as the coarse RMA content increased, the resulting weighed water absorption of the total aggregate mass increased and thus the resistance to chloride ion penetration decreased.

González & Etxeberria[76] studied the properties of concrete with increasing coarse RCA content, sourced from concrete with compressive strengths of 40 MPa, 60 MPa and 100 MPa on the properties of 100 MPa concrete. As expected, the total charge passed increased with increasing RCA, the degree of which increased as the strength of the RCA's source concrete decreased (increases of 50%, 114% and 140%, when using 100% coarse RCA). A similar trend was observed by Kou et al.[81].

It is possible that crushing causes internal micro-cracks in RCA thus leading to a more porous microstructure. Xiao et al.[98] concluded that the width of the cracks in the old adhered mortar is correlatable with the chloride diffusion coefficient, i.e. diffusivity increased as the crack width increased; therefore, as the RA content increases, RAC becomes more permeable.

Pedro et al.[85] studied the influence of the RA's crushing procedure 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. Mixes with RCA-2 showed strength improvements between 7% and 15% in comparison to mixes made with RCA-1. This trend was also noticeable in the chloride ion penetration of concrete. Using RCA-1 caused chloride ion penetration increases of 4.1% and 17.9%, for concrete mixes with target strengths of 45 MPa and 65 MPa, respectively, whilst when using RCA-2 this increase was just 1.6% and 7.8%. This trend was also observed by Moon et al.[55], who compared the chloride ion penetrations of concrete with RCA subjected to jaw crushing and impact crushing stages only, and a RCA that also underwent wet grinding.

Kou & Poon[49] studied the properties of concrete made with polyvinyl alcohol (PVA) impregnated RCA. This treatment improved compressive strength, when compared to that of mixes with untreated RCA, and also the resistance to chloride migration. Untreated RCA caused a chloride ion penetration increase close to 60%, while PVA-treated RCA resulted in equivalent total charge passed when compared to that of the control NAC.

### *3.3. Exposure to different curing conditions*

Amorim et al.[39] studied the influence of curing condition on the durability-related properties of concrete mixes with increasing coarse RCA. They observed that when RAC specimens were cured in relatively drier environments (laboratory environment with an average relative humidity of 60% and temperature of 20 °C), for a period of 91 days, they showed 35% higher chloride ion penetration, while for the same replacement level (100% coarse RCA), RAC mixes cured in a wet chamber exhibited 23% higher chloride ion penetration.

Kou et al.[50] and Poon et al.[57] studied the effect of applying a steam curing regime to specimens with increasing coarse RCA content. Steam-cured specimens showed an average of 20% and 30% less chloride ion penetration at 28 and 90 days, respectively, than mixes subjected to standard curing. The combined effect of steam curing and the introduction of 35% fly ash as cement replacement further enhanced the resistance to chloride ion penetration. Specimens with 100% coarse RCA in these conditions exhibited 54% and 72% less total charge passed at 28 and 90 days, respectively, than that of control NAC subjected to standard curing and without fly ash.

### *3.4. Influence of the mixing procedure*

Normally, in conventional concrete mixes, aggregates are placed in the mixer in a dry state, since their water absorption is generally very low (normally between 0.5% and 1.5%), and therefore relatively little water is required to compensate the water absorbed by the NA during mixing. However, because of the RCA's high water absorption, due to the old cement mortar adhered to its surface, RCA should be incorporated in saturated and surface-dried conditions[21].

Leite[99] proposed the use of a simple water compensation method that can be applied during concrete mixing, as an alternative to pre-saturating RA 24 hours prior to mixing. Since then, several authors[39,40,89,100-106], who have used this method, produced RAC mixes with minimum strength loss and equivalent workability to that of the control concrete, regardless of the replacement level.

A slightly different approach for the production of RAC was proposed by other researchers[44,107-109], the concept of which is similar to the one previously mentioned. Instead of the normal mixing approach (NMA), in which all components are placed inside the mixer at the same time, the authors proposed dividing it in two stages (two stage mixing approach - TSMA). Tam & Tam[44] studied the chloride ion penetration of concrete mixes made with increasing coarse RCA content produced with the NMA and TSMA. NAC and 100% coarse RCA specimens made with the TSMA exhibited 16% and 11% lower total charge passed, respectively, than those of the same mixes using the NMA.

Kong et al.[79] proposed another procedure, similar to the aforementioned, but with a new stage, in which the saturated and surface-dried aggregates are mixed with mineral additions. This method allowed producing RAC mixes with equivalent compressive strength and total charge passed when compared with the control NAC made with the NMA.

### *3.5. Effect of using admixtures*

Due to the relatively high water absorption and rougher surface 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 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[110].

Cartuxo et al.[73] evaluated the durability-related properties of concrete with increasing fine RCA content and superplasticizers with different water-reducing capacities. After 91 days, specimens with 100% fine RCA exhibited migration coefficient increases of 41%, 46% and 56% when compared with control NAC mixes without admixtures, with a regular water reducing admixture and with a high range water reducing admixture, respectively.

Matias et al.[111] studied the effect of different superplasticizers on the performance of concrete with coarse RCA. The results showed that by simply using a high range water reducing admixture, concrete with 100% coarse RCA showed 20% lower migration coefficients than the control NAC without admixtures.

Zhu et al.[112] investigated the influence of using silane-based water repellent as an admixture and as surface treatment on the durability-related properties of RAC. As expected, the compressive strength of RAC with 100% coarse RCA was lower than that of the control NAC (18% decrease), which decreased even further after adding 0.5% of silane (NAC and RAC with this admixture showed 41% and 38% less compressive strength than the respective mixes without silane). However, the resistance to chloride ion penetration increased with this treatment; 100% coarse RAC specimens with surface treatment (200 g/m² of silane paste) and with silane emulsion as an admixture (1% by weight of cement) total charge passed decreased 55% and 10%, respectively, in comparison to that of the untreated NAC.

### *3.6. Chloride ion penetration over time*

Kou & Poon[82] studied the influence of increasing coarse RCA and fly ash content on the long term properties of RAC. Figure 2 plots the total charge passed of concrete specimens exposed to an outdoor environment. 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/m³. Over time, the chloride ion penetration of RAC is parallel to that of the corresponding NAC. Increasing coarse RCA content decreased the resistance to chloride ion penetration at all test ages. Specimens with 100% coarse RCA showed increases in total charge passed between 10% and 21% when compared to those of corresponding NAC mixes. However, after 10 years, specimens showed negligible differences between them in terms of resistance to chloride ion penetration.

### *3.7. Effect of mineral additions*

#### 3.7.1. Fly ash

Normally, as the alumina content increases, the total charge decreases[113]. Fly ash, which contains high alumina content, may trigger pozzolanic reactions with the cement

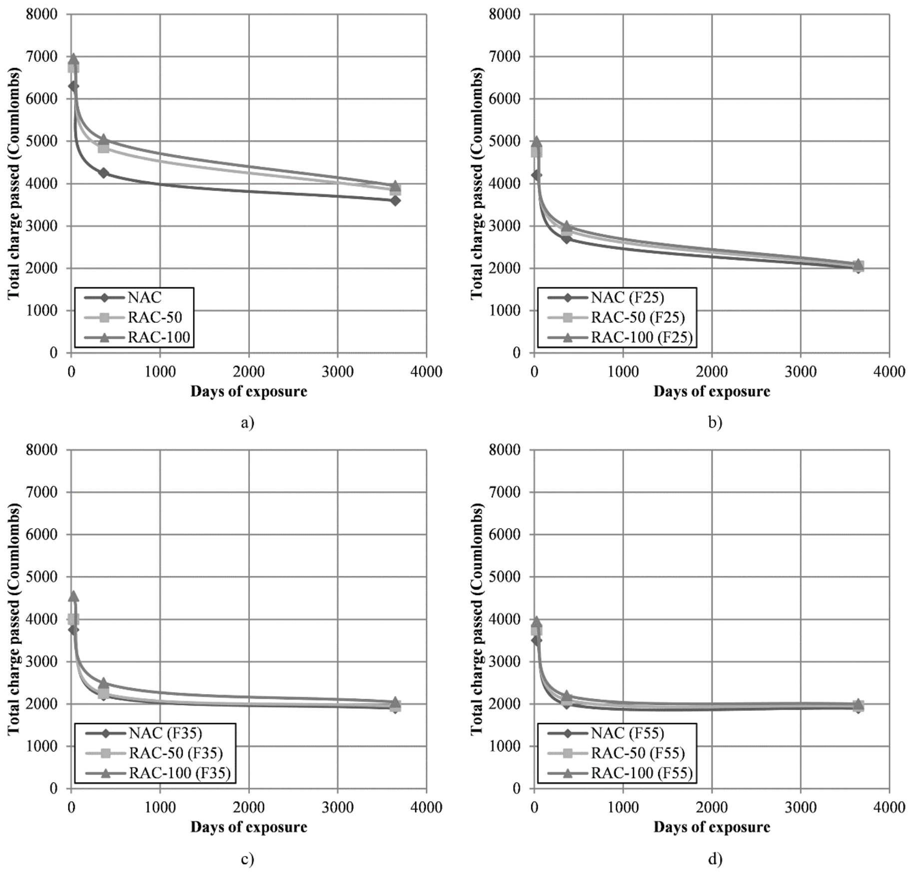


**Figure 2.** Total charge passed over time of concrete mixes with varying coarse RCA and fly ash content (F) of: a) 0%; b) 25%; c) 35%; d) 55%[82].

resulting in the formation of a greater and denser calcium silicate hydrate (CSH) structure and $C_3A$, capable of chemically binding chloride ions[113-115].

Several researchers[46-48,50-54,59,74,87,116,117] have studied the effects of fly ash on the chloride ion penetration of RAC. As expected, the review on this subject shows that increasing fly ash content leads to greater resistance to chloride ion penetration.

Figure 2b, c, and d show the effect of adding various amounts of fly ash on the chloride ion penetration over time[82]. The effectiveness of fly ash is demonstrated by comparing the results of the mixes 28 days after casting. Concrete mixes with 25%, 35% and 55% fly ash exhibited 28%, 33% and 43% less total charge passed, respectively, than that of the corresponding 100% coarse RCA mix without fly ash. After 10 years, regardless of the replacement level, all mixes produced with fly ash exhibited almost 50% less charge passed than mixes without additions. Furthermore, the increase of fly ash content makes the detrimental effect of RCA incorporation less pronounced after just one year exposition to an outdoor environment. As adding fly ash to concrete mix is usual when resistance to chloride penetration is required, this indicates that the use of RA will not represent a problem to concrete behaviour in this respect.

### 3.7.2. Silica fume

The effect of silica fume on the chloride ion penetration of RAC was also studied by some researchers[54,55,67,74]. The analysis of the literature suggests that the use of this material in concrete increases resistance to chloride ion penetration. The data retrieved from these publications showed that adding 10% silica fume by weight of cement led to 15% to 80% less chloride ion penetration than occurred in mixes without additions.

### 3.7.3. Metakaolin

Moon et al.[55] found that, by adding 10% by weight of cement of metakaolin, the total passed charge was 63% lower than in mixes without additions. However, when Kou et al.[54] added 15% metakaolin, the average improvement was only 26%, as displayed in Figure 3, which plots the total charge passed of concrete mixes with increasing coarse RCA content and different mineral admixtures. Although the initial concrete mixes had a high susceptibility to chloride ion penetration, after various mineral admixtures were introduced in different amounts the mixes easily showed moderate resistance to chloride ion penetration. The results of this study reinforce the notion that the effect of use of additions mitigates the effect of using recycled aggregates.

Vaishali & Rao[60] studied the effect of introducing both coarse and fine RCA and metakaolin as an addition on the chloride ion penetration of fibre reinforced high performance concrete. Adding metakaolin greatly improved resistance to chloride ion penetration. However, fully replaced RAC and with 100% coarse RCA showed 74% and 65% greater total charge passed, respectively, than that of the NAC. As the fibre content increased, so did the resistance to chloride ion penetration; introducing 1.25% reduced total charge passed by 35% to 45%.

### 3.7.4. Ground granulated blast furnace slag

Table 3 presents the data obtained from publications[54,116,118] which analysed the influence of the presence of ground granulated blast furnace slag (GGBS) on the resistance to chloride ion penetration of RAC. The results show that the use of 50% to 70% of GGBS by weight of cement may reduce chloride ion penetration by between 18% and 56%.

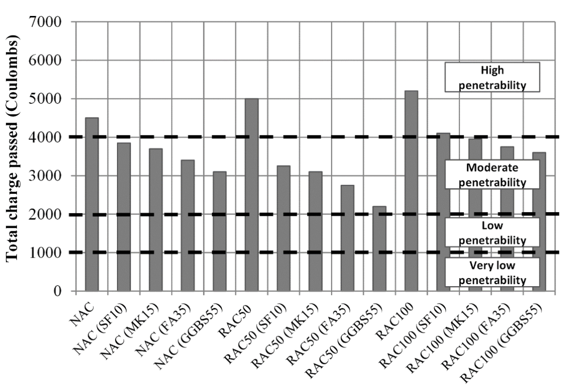


**Figure 3.** Total charge passed at 28 days of concrete with varying coarse RCA content and different additions (adapted from Kou et al.[54]).

**Table 3.** Effect of adding GGBS on the chloride ion penetration of RAC.

| Reference | Mix code (w/b; RA content) | GGBS (% by weight) | Improvement |
|---|---|---|---|
| Ann et al.[116] | RAC (0.45; 100% coarse RCA) | 65 | 18% |
| Berndt[118] | NAC (0.40) | 50 | 53% |
| | | 70 | 53% |
| | RAC (0.40; 100% coarse RCA) | 50 | 50% |
| | | 70 | 41% |
| Kou et al.[54] | NAC (0.50) | 55 | 31% |
| | RAC (0.50; 50% coarse RCA) | 55 | 56% |
| | RAC (0.50; 100% coarse RCA) | 55 | 31% |

## 4. Prediction of the Chloride Ion Penetration of Recycled Aggregate Concrete

Figure 4 presents the relationship between the chloride migration coefficient, calculated as per NT Build 492[38], and the 28-day compressive strength of RAC specimens, the binder of which is equivalent to CEM I[27]. It contains 245 measurements, taken after a curing period of 28 days, sourced from 9 publications[39,40,61,72,73,78,84,85,89]. The results were analysed in terms of: a) coarse RCA replacement level; b) size; c) type and; d) class[90]. Individual assessments of Figure 4 suggest that the aforementioned factors have little influence on the relationship between the migration coefficient and compressive strength, despite playing a great role on the properties of RAC relatively to those of the control NAC.

Figure 5 presents the same relationship as in Figure 4, but divided by testing age and with 95% confidence limits in place. It is clear that for the same compressive strength the relationship between the 91-day migration coefficient and compressive strength follows a slightly lower and parallel development to that of the 28-day readings. The coefficients of determination ($R^2$) for mixes tested at 28 days and 91 days are 0.778 and 0.823, respectively. This means that 78% and 82% of the variance in the response variable can be explained by the explanatory variables. The remainder may be explained due to a number of factors, which vary in each experimental investigation. These include compaction and curing conditions of concrete, cement content, w/c ratio, and the porosity of RA. Furthermore, according to Piaw[119], the coefficients of correlation (R) show that there is a very strong correlation between the two variables. A similar analysis (Figure 6) was performed with the total charge passed of RAC mixes produced with binder equivalent to CEM I[27], based on 123 measurements sourced from 16 publications[44,46,50-54,57,59,60,75-77,81,82,87]. As in Figure 4, factors related to the use of RA in concrete, known to have a significant influence on the resistance to chloride ion penetration, appear to have had marginal effect on the relationship between the total charge passed and compressive strength.

Given these results, it is possible to estimate the chloride migration coefficient and total charge passed of RAC mixes regardless of replacement level, type, size and class. Table 4 presents statistical indicators, the regression curve as well as the 95% confidence intervals for Figure 5b and 6b, which present the 28-day readings of concrete specimens made with coarse RA and binder equivalent to CEM I. The coefficients of correlation show that there is a strong correlation between the explanatory variables[119].

Having obtained such strong correlations between these properties and compressive strength, the authors then proceeded to isolate the variable $f_{cm}$ to understand the relationship between the values obtained in the two testing methods. Although important, this relationship has not been the object of many studies. Figure 7, which shows the chloride migration coefficient *versus* total charge passed, suggests that there is a linear relationship between them.

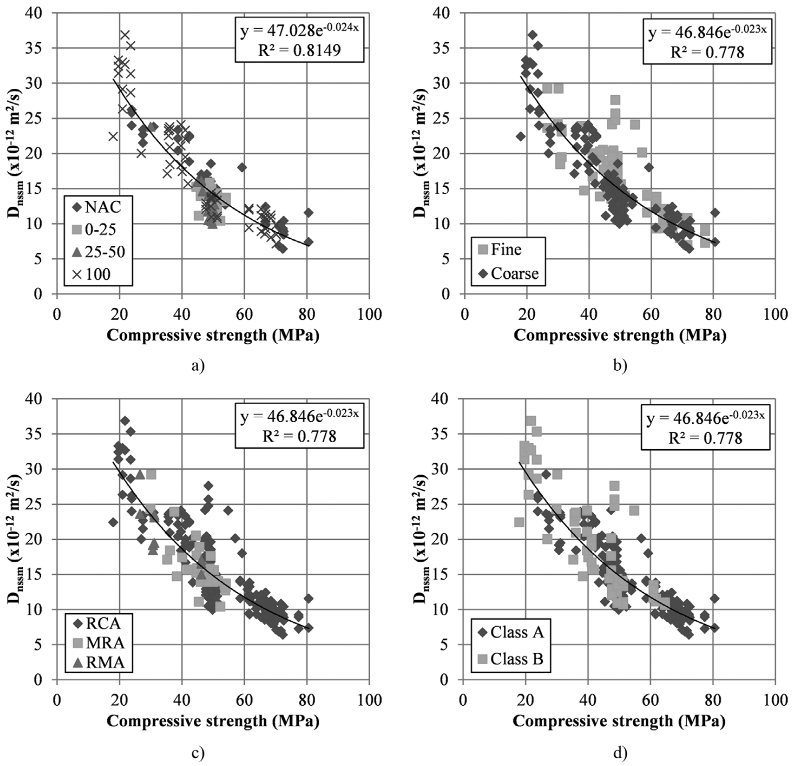


**Figure 4.** Relationship between chloride migration coefficient and compressive strength as a function of replacement ratio (a), RA size (b), RA origin (c) and RA quality (d).

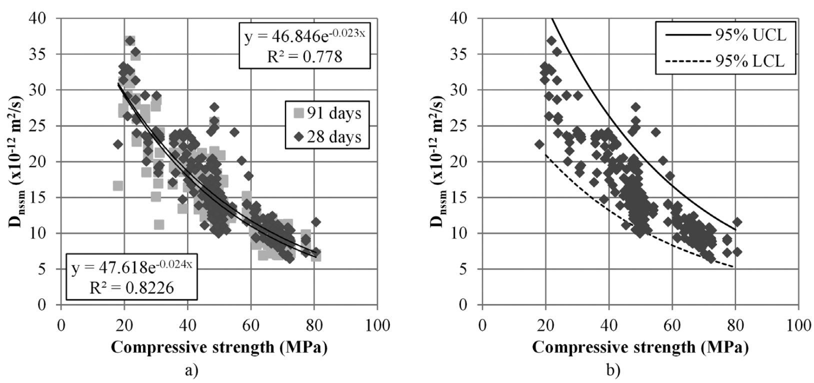


**Figure 5.** Relationship between chloride migration coefficient and compressive strength.

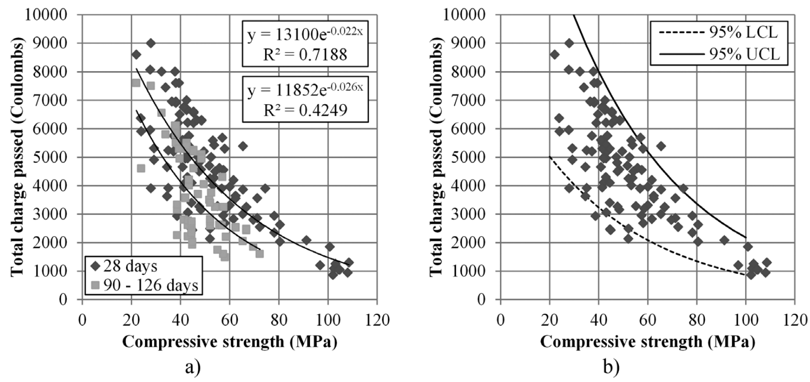


**Figure 6.** Relationship between total charge passed and compressive strength.

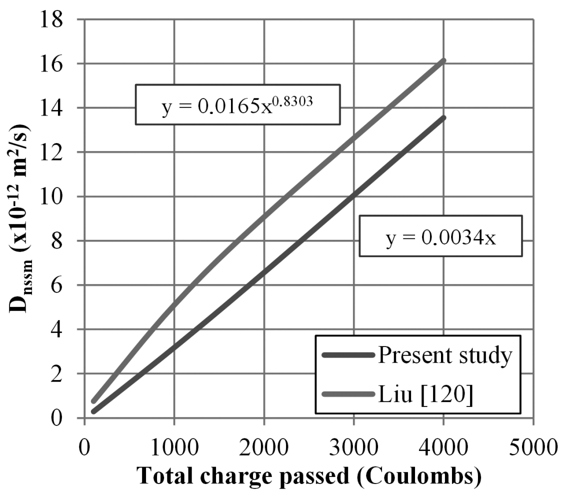


**Figure 7.** Relationship between chloride migration coefficient and total charge passed.

**Table 4.** Relationship between chloride migration, total charge passed and compressive strength.

| Test method | NT Build 492[38] | ASTM C1202[34] |
|---|---|---|
| $R^2$ | 0.778 | 0.719 |
| R | 0.882 | 0.848 |
| Regression | $46.846 \cdot e^{-0.023 f_{cm}}$ | $13100 \cdot e^{-0.022 f_{cm}}$ |
| 95% UCL | $66.276 \cdot e^{-0.023 f_{cm}}$ | $19047.735 \cdot e^{-0.022 f_{cm}}$ |
| 95% LCL | $33.112 \cdot e^{-0.023 f_{cm}}$ | $7784.921 \cdot e^{-0.022 f_{cm}}$ |

**Table 5.** Maximum allowable chloride migration coefficients.

| Environmental class[129] | Chloride migration coefficient[38] ($x10^{-12}$ $m^2/s$) | |
|---|---|---|
| | fib[127] | Portuguese[128] |
| XS1 | 3.5 | 11.3 |
| XS2 | 2.3 | 10.7 |
| XS3 | 2.9 | 3.2 |

When compared to the exponential relationship obtained from the results of Liu[120], who tested concrete specimens using the same testing methods referred in this study, it is clear that there is a similarity between them.

## 5. Chloride Induced Corrosion of Reinforced Recycled Aggregate Concrete

Reinforcing steel corrosion is the most common deterioration mechanism in reinforced concrete structures[121-123] and is usually induced by concrete carbonation or chloride penetration. Actually chloride induced corrosion is a more severe deterioration mechanism[124], especially in marine environments[125]. Therefore, concrete resistance to chloride ingress is paramount information within a service life prediction context.

The service life of a structural component is the period after construction when all the properties exceed the minimum acceptable values when routinely maintained[126]. A fib task group has developed an analytical model to simulate structures behaviour under external chloride attack[127] and there is also a similar model[128], developed by the Portuguese Laboratory of Civil Engineering. Both models are part of approaches that comprise reliability concepts and allow establishing performance requirements, namely in terms of the chloride migration coefficient[38].

Assuming the validity of the aforementioned methodologies for RAC, with the use of a fast chloride penetration test, it is possible to estimate the required chloride ingress resistance of a reinforced RAC exposed to chlorides in natural (service) conditions.

Considering both methodologies, the reinforcement covers specified in Table 4. 4N of EN 1992[129] for a structural class S4 and an intended service life of 50 years, binder CEM I[27] and water-cement ratio of 0.4, the threshold values of the chloride migration coefficient, calculated as per NT Build 492[38], are presented in Table 5. Even though the Portuguese approach applies a semi-probabilistic (partial safety factors) calculation, it considers a cracking (due to corrosion products) limit state and a reliability index β = 1.5, while the fib approach uses a full probabilistic calculation, considers a depassivation limit state and a reliability index β = 1.3, the difference between required performance returned by both approaches is too high, with the values from calculations using the fib approach seeming too restrictive and too close to each other, considering the difference between exposure conditions. Bertolini[130], when using the fib approach for environmental class XS3, for concrete with ordinary Portland cement as binder, obtains reinforcement cover larger than 145 mm to achieve a target service life of 50 years.

Regarding the values returned from the Portuguese approach, 45% of collated RAC mixes with CEM I, which fulfil the limiting water-cement ratio and cement content for environmental class XS1, recommended in EN 206-1[26], comply with the required chloride migration coefficient. For environmental class XS2 there were 21%, while for class XS3 there were none. These figures indicate that RAC is a suitable material for reinforced concrete structures subjected to chloride induced corrosion (classes XS1 and XS2), as long as the RAC mixes meet the recommended limiting values in EN 206-1[26] for composition. For reinforced concrete exposed to environmental class XS3, the use of admixtures which enhance the concrete performance against chloride penetration (vide section 3.7) is foreseen, either for NAC or RAC.

## 6. Conclusions

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

- The literature review suggested that the incorporation of coarse RA leads to higher chloride ion penetration depths (close to 100%), when compared to those of the corresponding NAC;

- As the porosity of the RA increases so does chloride ion penetration. This was found by comparing mixes made with RMA, RCA and MRA. As the RMA content increased, so did the chloride ion penetration;
- The use of an additional crushing procedure may help, producing RCA with better quality and thus RAC with better performance. The secondary crushing procedure normally produces aggregates with a more spherical shape, thus allowing better packing of concrete. When all mixes exhibit similar workability levels, the water content has to be reduced, which results 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;
- The microstructure of concrete becomes increasingly resistant to chloride ion penetration with the passage of time. Mixes with increasing coarse RCA content showed the same resistance to chloride ion penetration as the corresponding NAC mixes, 10 years after casting. This effect may be further improved by incorporating fly ash in the mix;
- Generally, the use of mineral additions was found to have a positive effect on the resistance to chloride ion penetration. This improvement occurred at a fairly similar rate in RAC with increasing replacement levels and in the corresponding NAC. This means that when incorporating a given addition, the expected improvement in RAC mixes is the same as the one expected in the corresponding NAC mixes;
- RAC mixes cured in progressively drier environments showed a higher sensitivity to chloride ion penetration. The use of steam curing could be a good way to increase the resistivity of a RAC. The combined use of this curing regime and fly ash is known to further enhance the resistance to chloride ion penetration;
- It is possible for RAC mixes to exhibit similar chloride ion penetration depths if the w/c ratio is adjusted. This method produces RAC with target strength and resistance to chloride ion penetration depths equivalent to those of the corresponding NAC;
- For the same compressive strength, RAC specimens exhibited a similar resistance to chloride ion penetration to that of NAC. This allows predicting the chloride migration coefficient and total charge passed solely based on their strength class, consequently facilitating the design of concrete structures exposed to more aggressive environments;
- The use of the service life design approaches showed that RAC mixes meeting the recommended limiting values for conventional concrete mixes for XS1 and XS2 classes exhibit a resistance to chloride penetration adequate to accomplish the target service life; therefore, RAC is a suitable material for reinforced concrete structures subjected to those environments. 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 environmental classes XS1 and XS2, with given target service life and reinforcement cover.

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