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Review

Insights on the Corrosion Resistance of Reinforced Recycled Aggregate Concrete

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Abstract: Recycled aggregate produced from crushed waste concrete is suitable for use in structural concrete. It reduces the demand for non-renewable resources and also for energy in general. However, RA is more porous than most natural aggregates. The porosity of the concrete cover defines the corrosion resistance of reinforced concrete, and it is therefore disputed how the use of recycled aggregate may affect the durability of reinforced concrete. This paper describes the corrosion-related performance of reinforced concrete with recycled aggregates in the initiation stage (determined by the carbonation and chloride ingress) and propagation stage (determined by the electrical resistivity and cracking) of corrosion. The aspects of interest are not only the porosity of RA but also its effects on the chloride binding, carbonation, electrochemical properties and corrosion cracking development.

Keywords: recycled aggregate concrete; corrosion; carbonation; chloride ingress; durability

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1. Introduction

The corrosion of reinforcement depends on the physical and chemical protection that concrete cover can provide to the rebar [1]. Such protection is governed by the pore structure, chemical activity and depth of this concrete cover. Conventional concrete with an appropriate design has proved to provide sufficient protection to ensure that reinforced concrete structures have a suitable service life in marine and industrial environments. Sustainability goals require that future demand for new concrete be satisfied without the depletion of increasingly scarce non-renewable resources for use as aggregate. The use of alternative aggregates can affect both the physical and chemical capacity of concrete cover to protect reinforcement against corrosion.

The use of recycled aggregates (RAs) obtained from crushed concrete reduces the environmental impact of concrete production, while it valorises construction and demolition waste. As a recognised eco-efficient practice, it has been applied for several decades, mainly in the United States, Japan and Europe and increasingly in Latin America. After World War II, there was a great interest in waste concrete recycling due to the urgent need to rebuild infrastructure in the affected countries. By the end of the 1970s, 40 million tonnes of waste concrete had been reused in the former Soviet Union [2]. Japanese regulations for the use of recycled concrete date back to 1977, which allowed the recycling ratio of waste concrete in Tokyo to be as high as 56% by 1988 [2]. In Germany, the use of RAs has been part of the specifications for aggregates in general since 1998. Intensive infrastructure modernisation programmes have produced a significant volume of facilities built with RA concrete (RAC) since the early 1990s [2]. In countries with a shortage of natural aggregates (NAs) such as the Netherlands or Belgium, recycling rates exceed 80%, although only a fraction of these aggregates are used to make new concrete. Therefore, it is necessary to reliably expand the application of RAC.

RAs show differences from coarse NAs due to the paste or mortar attached to their particles [2–4]. In the literature, the content of hardened cement is represented by the content of attached paste in the case of fine RA or the content of attached mortar in the case of coarse RA. Additionally, similarly to how the properties of NA depend mainly on the characteristics of the original rock, the characteristics of RA are related to those of the source concrete [5,6]. It is generally agreed that RAs have a reduced performance in comparison with NAs, i.e., lower density, lower frost and abrasion resistances, more material finer than 75 µm and higher water absorption. As a result, the mix proportions and fresh and hardened properties of RACs are different from those of NA concretes (NACs) [7–9].

The influence of coarse RA on the mechanical properties of concrete has been extensively studied. In general, it has been concluded that replacing up to 30% of coarse NA with coarse RA does not produce significant changes in mechanical properties [7,10,11]. Furthermore, some studies [12,13] have indicated that even replacement ratios of up to 75% can produce negligible influences on the mechanical properties of concrete. The main differences between these studies and the others are the low porosity level and degree of contamination of the RA and the fine-tune correction of mixing water in the mix.

With respect to the durability performance of RAC, there is some disagreement in the literature. This is probably due to opposing effects on the pore structure. On the one hand, there is the improvement of the interfacial transition zone between the RA and the new mortar [14]; on the other hand, the higher porosity of these aggregates increases the total porosity of concrete. Then, the durability of RAC will be linked to the effect of the aggregate on related transport parameters, such as chloride ingress, carbonation, water and moisture transport and resistance to physico-chemical attack, such as sulphate attack or freeze–thaw. For each case, the predominance of an enhanced interfacial transition zone or higher porosity in comparison with NAC will explain the improved or decreased durability performance of RAC.

The transport properties of the concrete cover are of fundamental importance for the durability of reinforced concrete. The mass flow is mainly due to permeability (caused by a pressure gradient), diffusivity (due to a concentration gradient) and capillary absorption (caused by capillary suction). To prevent the corrosion of reinforcement, care should be taken to minimise the chloride ingress into the concrete cover in marine environments and to minimise the carbonation rate in other environments. Initially, the steel embedded in the concrete is in a passive state, but the drop in pH due to carbonation or the presence of chloride ions over the threshold content causes the passive layer to break down [15,16]. Moreover, for corrosion to occur at a considerable rate, the simultaneous presence of high relative humidity and oxygen in the medium is necessary. Therefore, the effect of RA on durability with respect to reinforcement corrosion is strongly linked to the way that it affects the transport properties of the concrete cover.

The purpose of the present review is to summarise all aspects of reinforcement corrosion that are directly and indirectly affected by the use of coarse and fine RA in concrete. We focus on binders based on pure or blended Portland cement (while geopolymer concrete is not particularly addressed due to its significantly different characteristics). Some factors are relatively obvious, such as the effect of the attached mortar on the overall porosity and mechanical properties, but the associated effects can be equally significant. The literature generally focuses on the physical effects, while more consideration of the chemical effects seems important, particularly with respect to the effects on carbonation and chloride penetration. The literature is more advanced for the case of coarse RA, while research on the effects of fine RA is still necessary. A summary of the state-of-the-art in all of these aspects follows.

2. Porosity and Moisture Transport Properties

RA has a higher absorption capacity (i.e., more porosity) compared to commonly used NAs [13]. Its use may increase the porosity of concrete, and this can be detrimental to the durability properties of reinforcement when favouring transport properties [5]. However, in some cases, the effect of RAs can be very small [17,18] and can be easily compensated by the action of supplementary cementitious materials [19]. While the transport properties of concrete are related to the pore volume of the material, even more important are the distribution and connectivity of the pores [20]. The pores connected to the exterior are the ones allowing the entry of harmful substances. Therefore, increasing the porosity of the concrete is not sufficient to judge the effect of RA on durability.

The porosity of the aggregate is important not only in hardened concrete but also during the production phase. Latent absorption by the aggregates plays a major role, as it is able to modify the free water content in the mix and thus decrease its workability. In the case of coarse RAs, this situation is relatively simple to solve. These aggregates can be first saturated in water, or the water absorption of the aggregates can be added to the mix, allowing them the necessary time to absorb before introducing the binders. In these cases, it is ensured that the effective water/cement ratio and free water content remain almost unaffected. In the case of fine RAs, the problem is a little more complex. On the one hand, the particle shape itself causes a higher water demand for a certain slump due to the increased internal friction of the granular skeleton [21]. On the other hand, the methods usually used to determine the absorption capacity of these fine RAs are not always effective. Eventually, the amount of free water can be unintentionally increased if too much compensation water is added. Therefore, aggregates can indirectly affect the durable properties of a structure by decreasing its workability and compactability.

Currently, methods for determining the absorption capacity of fine aggregates are reliable only for materials with rounded particles (natural sands). In contrast, methods for determining the saturated condition at the dry surface, such as the truncated cone method, result in significant errors when applied to crushing aggregates such as fine RA [20]. Faced with this uncertainty, it seems inconvenient to correct the water content of the mix for the total water absorption of the fine RA [22,23]. Since aggregates do indeed absorb a certain amount of water, a fraction (49–89%) of the water absorption capacity of the aggregate is generally applied in the literature. However, the accuracy of the available methods used to determine the water absorption of the fine RA is still a matter of debate. Much of the literature analysing and noting a very unfavourable effect of fine RA on the durability performance of concrete is not entirely convincing, considering that the effective water/cement ratio could have been unintentionally increased by the addition of the total estimated water absorption. In these cases, the mixes are incomparable to conventional mixes with aggregates of much lower absorption (and, therefore, a lower effective water/cement ratio). Sosa et al. [24] determined that the mechanical performance of concrete with fine RA is better correlated with the total water/cement ratio than with the effective water/cement ratio estimated upon consideration of the aggregate absorption. To avoid unintentional increases in the effective water-to-cement ratio, it seems sensible to incorporate fine RA in the air-dry condition and use a water-reducing admixture to compensate for slump loss [23].

Other durability studies [25,26] show that porous aggregate particles have a reduced impact when embedded in a low-porosity matrix. RAs allow the design of durable concretes when the design of the mix complies with the required performance for the matrix, and experimental studies have shown that this is largely feasible.

One additional aspect to consider from laboratory studies comparing RAC with NAC is that these studies generally involve extensively cured samples, i.e., with a high degree of hydration. This ignores a potential advantage of RA, which is more porous and could supply curing water if external curing is not applied [27–29].

3. Carbonation

The carbonation of concrete is a natural process that occurs when CO_2 in the surrounding environment penetrates through the porous structure of concrete and reacts with hydration products [1,15]. The precipitation of carbonates as a result of carbonation reduces the ionic strength of the pore solution and its pH. The high alkalinity of the pore solution is key to stabilising the passive layer formed on the steel surface or the reinforcement embedded in concrete. Thus, when the carbonation front reaches the depth at which the reinforcement is located, depassivation of the reinforcement occurs, and in the presence of oxygen and moisture, active corrosion takes place.

The carbonation resistance and related durable properties of RAC have been reported by several authors [14,30–32]. The effect of the RA on the durable performance has been mainly related to the increased total porosity of the mix, but several additional aspects need to be addressed as well. Carbonation occurs when carbon dioxide penetrates the concrete and reduces its alkalinity by binding and precipitating calcium and other alkalis in the form of carbonates. RA can affect carbonation in two important ways. On the one hand, mortar bonded to the aggregate particles increases the porosity of the mix and allows a higher rate of carbon dioxide transport [30–32]. For this reason, a reduction in the water/cement ratio is sometimes recommended when using RAs as a partial replacement of NAs [31,33]. It has also been recommended to limit the replacement percentage (e.g., to a maximum of 30% of the total coarse aggregate) to avoid significant effects of increased porosity caused by bonded mortar on the carbonation rate [34]. On the other hand, attached mortar can provide a certain amount of carbonatable hydration products that may contribute to the carbonation resistance by increasing the binding capacity of carbon dioxide in concrete. Despite the progress in addressing this issue, the carbonation resistance of concrete with RA seems to have not yet been fully resolved.

Carbonation is of practical interest not only because it may lead to the corrosion of the reinforcement but also because it produces changes in the microstructure of the concrete. Some of these microstructural changes can be considered positive. When using ordinary Portland cement, precipitated carbonate reduces the pore connectivity and the transport properties of the concrete. This particular aspect should be noted for RAC, as uncarbonated attached mortar can also benefit from this process, and the relative impact of carbonation in RAC can be greater (in relative terms) than for NAC (with the same water-to-cement ratio). In concrete with a high content of supplementary cementitious materials, the issue is somewhat different. The depletion of portlandite caused by the concurrent pozzolanic reaction and carbonation causes the structure of the calcium silicate hydrate to deteriorate due to decalcification, weakening the microstructure of the concrete. For example, Arredondo-Rea et al. [35] showed that despite the improvement in porosity, RA mixes containing SCMs carbonate faster than mixes without SCMs (e.g., 30% increase for fly ash). Therefore, the problem of carbonation is more complex than the sole determination of the porosity of RAC.

For the prediction of the carbonation rate, empirical relationships with mechanical properties at 28 days are generally considered. In fact, performance-based design for durability generally considers such properties to stipulate the requirements for the concrete mix. In the study by Zega et al. [36], the correlation between carbonation coefficients of RACs and 28-day properties was determined. The capillary absorption coefficient as a predictive index for carbonation is generally considered a suitable design tool by durability guidelines. The use of RA complies with the trend of this relationship, but a more specific relationship is desirable for RAC. A low capillary absorption coefficient is indicative of concrete with high resistance against carbonation, even if RAs are used in the mix. Conversely, compressive strength appears to be a very weak descriptor of the effect of RA on the carbonation performance of concrete. This reflects the fact that the carbonation rate is not solely determined by the pore volume. These findings were precisely indicated by Silva et al. [31], who related the influence of RA on carbonation resistance to the pore volume that the RA provides to the mix. The results reported by Zega et al. [36] suggest that, under natural exposure, attention should be paid to the pore size range, as sorptivity was demonstrated to be a better descriptor than compressive strength.

Several multifactorial models have been proposed to predict the carbonation rate of RAC [37–39]. These models consider similar environmental effects to those addressed in models for NAC and incorporate material parameters such as the replacement ratio of RAC and the water absorption of RA. However, recent machine learning models demonstrated that cement content in RAC is a much more important factor than the replacement ratio and water absorption of RA [40]. Strategies to also consider the effects of stresses [41], in relation to the initial compression of the pore structure and subsequent microcracking, and the interaction with supplementary cementitious materials [42,43] have also been proposed. Significant research efforts are still necessary to move forward from the current empirical model to fundamental models based on reactive transport of CO_2 in RAC.

4. Chloride Ingress

The durability of reinforced concrete in the marine environment or exposed to de-icing salts depends on the resistance of the concrete to chloride ingress, as this leads to pitting corrosion. When there is a sufficient chloride content, i.e., threshold content, a localised rupture of the passive layer occurs. The chloride penetration into concrete then defines the duration of the initiation period for the reinforcement corrosion. The resistance of concrete to chloride penetration is mainly achieved by reducing the porosity of concrete [44,45].

Part of the chloride penetrating the concrete can be bound in the cement matrix. The chloride binding capacity of the matrix is a non-linear function of the total chloride content, and it is related to the amount of hydration products [46] and the late formation of hydration products [47]. As the retention of chloride in concrete reduces the amount of free chloride, its influence on the initiation of corrosion is twofold [48]: (1) the rate of ionic transport in concrete is reduced, and (2) the amount of free chloride that accumulates on the surface of the reinforcing steel and promotes pitting is reduced. Therefore, chloride ingress patterns are significantly dependent on the assumed retention ratio between free chloride in the concrete pore solution and the chloride retained in the hydration products [49]. The ratio between bound and free chloride is not permanent, as in addition to the bound chloride content, the pH of the medium [43] (more precisely, the amount of free hydroxide ions), temperature, relative humidity and the presence of other anions also play a role [50].

Regarding the influence of RA on chloride penetration, different results can be found in the literature. While some authors concluded that the use of coarse RA increases the chloride penetration rate [5], others reported that the differences between conventional and RACs are negligible [17,51], even when 100% of coarse RA is used [7,14].

Most research in this respect consists of immersing the concrete in NaCl solution (generally 30 g/L concentration) to simulate exposure. Although such an accelerated laboratory test is useful for quantitative characterisation of the chloride ingress resistance, it is not fully representative of marine atmospheric exposure (affected by environmental variations) or structures exposed to de-icing salts (under cycles of seasonal chloride loading and wetting and drying). Variations due to rainfall events, wind and time-varying surface chloride concentration are influential conditions for unsaturated concrete [52]. In addition, the presence of sulphate in seawater can reduce the chloride binding capacity compared to exposure to pure NaCl solution [53]. Moreover, structures in road environments exposed to de-icing salts are subject to additional CO_2 sources that favour carbonation and reduce the chloride binding capacity of concrete [54]. Therefore, it is important to complement accelerated laboratory assessments with long-term studies in conditions of marine exposure or wetting–drying cycles with de-icing salts.

In [51], the relative influence of several variables on chloride penetration in the marine environment and in NaCl solution was addressed for coarse RA. The porosity of the RA played a role when $w/b \leq 0.35$, where the chloride penetration was up to twice as deep as that of NAC (same w/b). However, for $w/b \geq 0.40$, the RA showed no noticeable influence. While the chloride penetration rate was higher in the RAC, an increase in chloride binding capacity due to the attached mortar was also noticed. Therefore, there is a certain compensation of porosity by the hydration products in the RA particles (i.e., an increase in porosity with RA content does not translate to a proportional increase in the chloride penetration rate relative to NAC).

Exposure to de-icing salts has the added complexity of a combined attack by freeze–thaw cycles and chloride penetration. The effect of RA on such performance can be reduced by the inclusion of an appropriate dose of air-entraining agent [55,56], just as in the case of NAC. Moreover, air entrainment not only improves the performance against freeze–thaw but also reduces the penetration of chlorides when the capillary network is disconnected by the entrained voids [57]. Therefore, no impact of RA is to be expected in concrete exposed to de-icing salts, as the requirements for these mixes to be resistant to freeze–thaw involves a very compact matrix that encapsulates aggregate particles and limits their significance.

In related research [58], it was shown that the type of NA that constitutes the concrete being recycled also has an important role. The petrography and texture of the aggregate generate significant differences in the interfacial transition zone. In agreement with the results in [51], for a coarse RA content of 25%, similar chloride ingress profiles were obtained in NAC and RAC with the same w/b. When the replacement percentage was increased to 75%, in cases where smooth textured aggregate (e.g., gravel) was replaced by RA, some improvement was even noted, attributed to improvements in the interfacial transition zone. A higher chloride binding capacity of RAC compared to NAC (same w/b) was also observed in [58], again associated with a higher content of hydration products. The attached mortar content and its properties are highly dependent on the characteristics of the original concrete from which RA is derived [6], so it is expected that the increase in chloride binding capacity by the RA will be variable.

Regarding chloride pitting due to chlorides, Villagrán Zaccardi et al. [59] showed that depassivation does not correlate with the inclusion of coarse RAs, as it depends on the threshold chloride content in the same way as in NAC. That is, no effect of RA content on the chloride threshold content has been determined.

5. Electrochemical Measurements on RAC

Numerous methods based on electrochemical techniques for the evaluation of corrosion development in reinforced concrete are available in the literature. The measurement of the polarisation resistance is very common in reinforced RAC, as is the case for any other type of reinforced concrete. Moreover, increasing attention is focused on the value of the electrical resistivity of concrete and electrochemical impedance spectroscopy.

The electrical resistance is defined as the ratio between the applied voltage and the electrical current flowing through a sample. The resistance to the passage of electric current defined per unit area and length is referred to as resistivity. The resistivity of the concrete cover helps to determine the risk of corrosion of embedded steel. The high repeatability of the method has led to its correlation with the corrosion performance of reinforced concrete. Its inclusion in the standards UNE 83988-1:2008 [60] and prEN 12390-19 [61] exemplifies its wide acceptance. Four ranges can be classified based on the conventional resistivity of concrete: <100, 100–500, 500–1000 and >1000 Ωm [62], for which the risk of corrosion of the reinforcement is classified as high, moderate, low and negligible, respectively. An important consideration is to differentiate bulk resistivity from surface resistivity (as determined by the Wenner method), as the values from the two methods follow the same trend, but they are not directly comparable [63].

The resistivity of concrete in the saturated state is an inverse function of the porosity of the material and the conductivity of the pore fluid. Since the use of RA does not noticeably change the pore fluid conductivity of concrete, it is logical that an aggregate with higher porosity, such as RA, would linearly decrease the resistivity of concrete [64]. Numerous studies agree on this decreased resistivity with the incorporation of RAs [65–75] (Figure 1). When incorporating RAs, the reduction in electrical resistivity indicates an effect on the interconnection of pores in the concrete. The formation factor relates the resistivity of the concrete to the resistivity of the pore fluid according to Archie's law [76]. The overall formation factor of concrete increases with the RA content, but the formation factor for its paste phase only slightly increases [68]. This means that while attached mortar increases pore connectivity, the dynamic absorption effect of RA can significantly improve the interfacial transition zone with the new matrix. The differences in electrical resistivity between NAC and RAC (same w/b) appear to increase with age up to 28 days [70], and they progressively decrease for later ages [67]. The decrease in the influence of the use of RA at later ages could be connected to the fact that the pore structure decreases with time due to the progression of hydration products, and the influence of the embedded aggregate porosity becomes less significant.

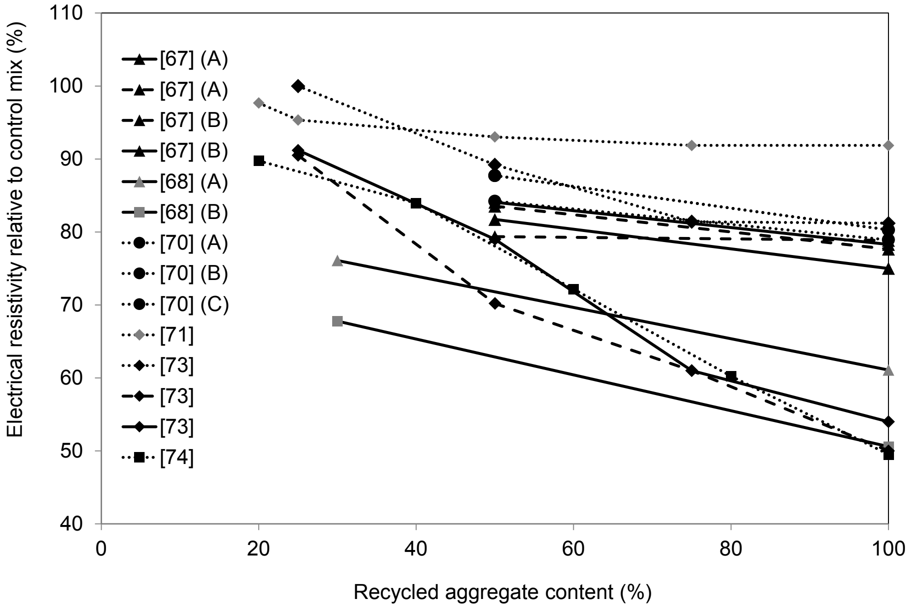
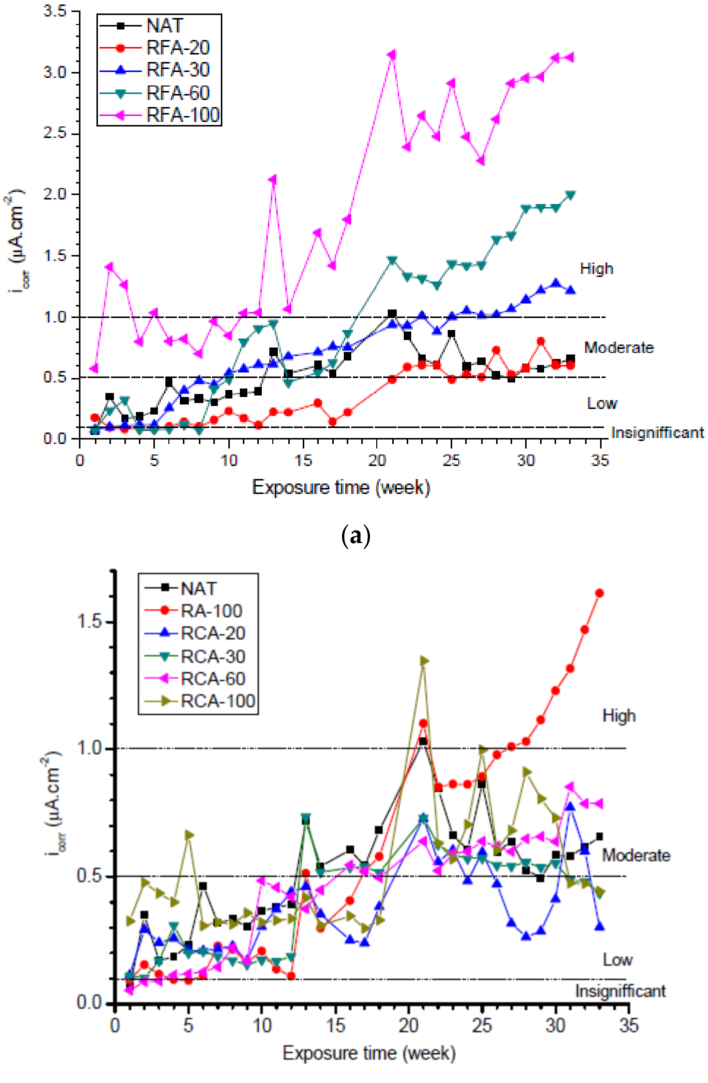


Figure 1. Effect of RAs on the electrical resistivity of concrete. Solid lines indicate the use of the fine and coarse RA together. Dotted lines indicate the use of coarse RA only. Dashed lines indicate the use of fine RA only.

Kurda et al. [67] concluded that the use of fine RA decreases the electrical resistivity compared to control concrete to a greater degree than coarse RA. This greater influence of fine RA was also reported in [63,75]. When using fine (50 and 100%) and coarse (50 and 100%) RA, Kurda et al. [67] and Sasanipour et al. [73] reported similar electrical resistivity to that when using only fine RA. The larger effect of fine RA may be due to its higher porosity compared to the coarse fraction. As previously mentioned, this higher porosity could also be related to an unintentional increase in the effective w/c ratio due to overcompensation of the water absorption of the fine RA [23]. There is no clear explanation for the lack of cumulative influence of the sum of fine and coarse RA.

To mitigate the decrease in electrical resistivity with the use of RA, the use of supplementary cementitious materials has proven to be efficient [67,73,77–79]. The pore refinement produced by the pozzolanic reaction increases electrical resistivity and improves the overall durability performance of RACs.

The lower resistivity increases the corrosion rate of active reinforcement when concrete contains sufficient moisture [64,80,81]. The effect is more significant for fine RA than for coarse RA in relation to their relative effects on the electrical resistivity of the concrete cover. Figure 2 shows examples of the increase in the corrosion rate due to chlorides, determined by the polarisation resistance method in reinforced concretes with variable contents of fine RA and coarse RA.



(**a**)

(**b**)

Figure 2. Effect of RAs on the corrosion rate of reinforced concrete exposed to wetting and drying cycles in 35 g/L NaCl solution for: (**a**) fine RA and (**b**) coarse RA. NAT is the control concrete, and RFA (fine) and RCA (coarse) are concretes with RA. The numbers indicate the percentage replacement ratio, and RA-100 is concrete with 100% content of both fine and coarse RA. Reprinted with permission from Ref. [64]. 2019, MDPI.

The straightforward interpretation that a lower resistivity in the saturated state implies a higher probability of corrosion is not accurate for all scenarios. Concrete that is not in direct contact with water will develop a hygroscopic equilibrium with the surrounding medium based on moisture condensation in its internal porosity. This makes it necessary to check the resistivity in the unsaturated state to determine the probability of corrosion in most structures. This measurement is not simple and requires special techniques [80], which is the reason that it is generally not addressed in most studies on the subject.

Significant potential and increasing application are observed for electrochemical techniques with AC. These are based on measuring the response of the material to AC stimuli over a range of frequencies, using simplified impedance circuits to interpret the results. For example, the electrochemical impedance spectroscopy (EIS) technique is based on analysing the impedance spectrum as a function of frequency. Several models have been proposed to interpret the results [82–86]. The main difficulty lies in the overlapping effects (bulk properties of concrete, formation of corrosion products, resistive product layer on rebar surface) that can be observed in the output of this method.

There are still few studies in the literature that apply the EIS technique to concretes with RAs. Corral-Higuera et al. [87] and Arredondo-Rea et al. [88] present comprehensive studies on the electrochemical properties of RAC and with different supplementary cementitious materials in their compositions. Using the EIS technique, the parameters R_{ct} (charge transfer resistance) and R_e (electrolyte resistance) were obtained, and i_{corr} (current density) and ρ (concrete resistivity) were calculated using the Tafel equations. The 100% coarse RA increases R_e (intersection in the curve at high frequencies) and slightly reduces R_{ct} (diameter of the arch) (Figure 3). This translates to lower electrical resistivity and higher i_{corr}. Nevertheless, the detrimental effect is very mild compared to the improvement achieved with low contents of supplementary cementitious materials, showing a practical compensation strategy. That is, concretes made with 100% RA, 30% fly ash and 10% silica fume showed even better electrochemical properties than the control concrete, especially at higher ages due to the pozzolanic effect. A similar compensatory effect was obtained when using 25% ground granulated blast-furnace slag as a partial replacement of cement in RAC [89]. Zhao et al. [90] reported the results of electrochemical measurements on concretes with different RA contents and related them to corrosion cracking generated by corrosion in twin specimens of the evaluated concretes. The results show a reduction in the resistivity of the concrete with increasing RA content, and this is mainly explained by the higher porosity induced by the use of RA in the new concrete. Thanks to the possibility of monitoring the electrochemical state of the steel–concrete system at different times, in this work, it was possible to determine the initiation time of the corrosion process, and a reduction was observed with increasing RA content. Arredondo-Rea et al. [88] explained the faster corrosion rate by the reduced resistivity of concrete with increasing RA content. However, it was observed that this reduction was considerably smaller for low replacement percentages (approximately <35%).

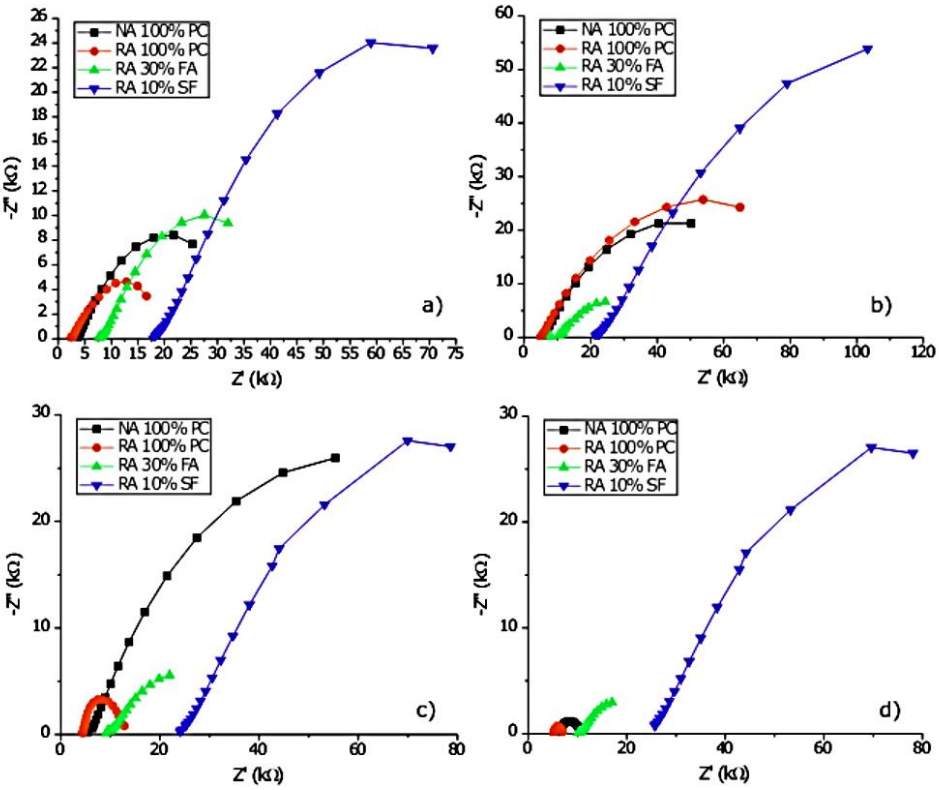


Figure 3. Effect of RAs, supplementary cementitious materials and time (REF): (**a**) 3 months, (**b**) 6 months, (**c**) 9 months, (**d**) 12 months. References: FA = fly ash; SF = silica fume, PC = Portland cement, NA = coarse natural aggregate; RA = coarse recycled aggregate. Reproduced with permission from Ref. [87]. 2011, ESG.

Electrochemical concrete measurement techniques offer the advantage of non-destructive evaluation of concrete structures. The evaluation of reinforced RAC with this technique is still incipient. The available data show similar trends to those determined for NAC with the same water-to-binder ratio; that is, a higher porosity (due to incorporation of RA) induces a greater corrosion rate in relation to the lower resistivity of the concrete cover.

6. Cracking Due to Corrosion

The development and propagation of active corrosion in RAC are different from those in NAC [91,92]. The use of RA introduces more interfaces, which accelerates the propagation of corrosion-induced cracks in the concrete cover [90]. However, steel corrosion and the corrosion-induced cracking of concrete are not significantly influenced by using low replacement ratios of coarse RA, e.g., 33% of the total coarse aggregate volume [90]. This may be because the reduction in the modulus of elasticity of concrete also improves its mechanical compatibility, and the stresses developed by the corrosion products are more easily relieved. That is, as RAC deforms more than equivalent NAC upon the formation of internal products, for a given volume of corrosion products that are formed, the achieved internal stress is lower. Moreover, a higher internal porosity of the concrete provides more space for the precipitation of corrosion products, and therefore, lower internal stresses are generated. The combined influence can lead to the delayed [93] or accelerated [94] appearance of corrosion cracking with the content of RA, depending on whether the main influence is through additional pore space for corrosion products (mainly for medium/high RA contents and high w/c ratios) or the shortening of the initiation period and introduction of weak interfaces (mainly for medium/high RA contents and medium w/b ratios). The additional space provided by increased porosity is an aspect that is difficult to investigate and model. There seems to be an optimum content of RA that favours the dissipation of stresses generated by corrosion products. Once this optimum replacement content is exceeded, the role played by the attached mortar and weak recycled interfaces can accelerate chloride ingress. These induce corrosion, and cracking is initiated earlier, independently of the amount of corrosion products that the cement paste may absorb. For example, Srubar III [95] considered the same ratio between the critical amount of corrosion products and the mechanical properties of the cover depth, independently of the RA content. With this simplification, the modelled time to corrosion cracking due to chlorides was reduced for 100% RAC relative to the control concrete, from 122 to 74 years in a mild chloride environment and from 19 to 14 years in a severe chloride environment. However, these results only apply to high replacement ratios, and the consideration of differences in the critical amount of corrosion product to produce cracking can better explain other experimental results in the literature.

The amount of attached mortar/paste in the RA plays a significant role in cracking development, as this is the phase that increases the overall porosity of the concrete. There is little information in the literature in this regard, but some predictions can be made based on the effect of the paste/mortar content on the mechanical and transport properties of the concrete. Srubar III [95] modelled the mortar content of RA particles by introducing an aggregate porous shell with a variable thickness to simulate the volume of attached mortar in the aggregate. This model can be used to depict not only the effect of the content of attached mortar but also the variations depending on the replacement ratio with RA (Figure 4). It is clear that the effect of the volume of attached mortar results in significant differences between low and high replacement ratios of coarse RA.

The more significant corrosion propagation rate not only reduces the working area of the reinforcement but also affects the bonding between reinforcement and concrete. Alhawat and Ashour [96] determined that the relative reduction in bonding due to active corrosion increases with the RA content. The faster degradation of the bonding was attributed to the faster corrosion rate due to reduced resistivity, with the effect of RA on mechanical properties playing only a secondary role (on the basis of the lack of effect of bonding in uncorroded samples). Thus, the effect of RA (contents >30%) on the corrosion propagation phase multiplies in comparison with the effect on the initiation phase.

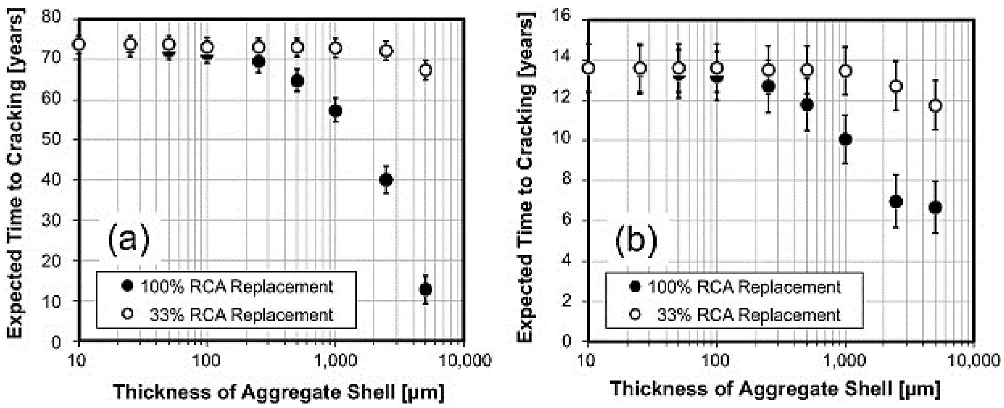


Figure 4. Effect of RA content, with variable thickness of aggregate shell (volume of attached mortar/aggregate specific surface): (**a**) concrete made with mildly chloride-contaminated (1 kg/m^3) RA and exposed to a mild chloride environment; (**b**) concrete made with severely chloride-contaminated (3 kg/m^3) RA and exposed to a severe chloride environment. Reproduced with permission from Ref. [95]. 2015, Elsevier.

Furthermore, when cracks occur, the modulus of elasticity of concrete plays a role in the geometry of the cracks. Figure 5 shows a conceptual diagram with the contrast between the geometry of cracks in NAC and RAC with the same w/b ratio. Initially, the lower strength of RAC will produce a smaller immediate crack opening (W_C^{RAC}) than in NAC. Afterwards, as RAC normally has a lower modulus of elasticity, the relaxation due to the appearance of the crack will result in a greater crack angle (θ_{RAC}) and crack opening (W_s^{RAC}) in RAC than in NAC.

Zhang et al. [97] also observed that the so-called corrosion-filled paste (CP) is wider for RACs (Figure 6a,b), suggesting that RA may have a greater ability to absorb corrosion products in the CP before the cracks reach the surface. This may also be due to an unintentional increase in the w/c ratio due to overcompensation of the water absorption of the aggregates [23] and may not necessarily be a direct effect of RAs. Zhang and Zhao [98] noted that in the presence of loading, CP tends to be thicker on the more stressed steel face and that cracks propagate preferentially towards the concrete cover side (Figure 6c,d), which would contribute to the formation of cracking.

In their study, Ortega et al. [99] determined the decrease in the first natural frequency of beams made with RA subjected to accelerated corrosion. The damage and drop in stiffness of these beams were more pronounced at the beginning of the cracking than at the end of the tests. Crack growth slows down as corrosion progresses in depth in the reinforcement, but this average attack depth on the reinforcement accelerates at the same time. The rapid loss of bonding between steel and RAC is mainly due to the high electrical conductivity resulting from its high porosity. Additionally, the increase in concrete cover depth is able to delay the onset of cracking and the total area of the cracks. This shows that there is no proportionality between cover depth and crack width, somewhat contradicting the model of Srubar III [95] (Figure 5). One possible explanation is the higher relative pressure induced by corrosion products with a greater cover depth, which means that for a given corrosion degree, greater amounts of corrosion products are required to generate cracks.

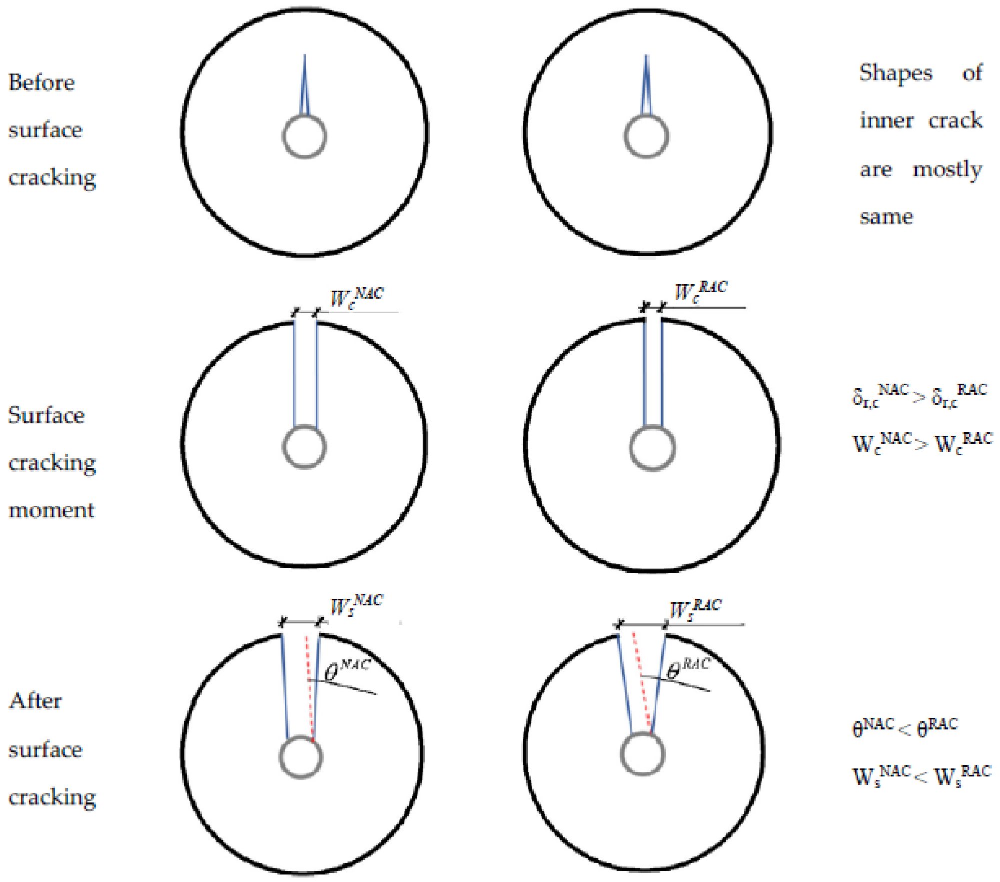


Figure 5. Propagation of corrosion-induced cracks in NAC (**left**) and RAC (**right**). Reproduced with permission from Ref. [100]. 2015, Elsevier.

Limited cracking development due to corrosion was also observed in [101] for RACs. The largest crack widths and the most accelerated crack growth were observed for beams with NAC, and these parameters decreased as the coarse RA increased from 0 to 100%. Thus, the development of corrosion cracking in RAC is not always directly affected by the increased porosity of the concrete.

Zhang and Zhao [98] studied cracking in beams with 0, 50 and 100% recycled contents subjected to chloride ingress and corrosion. Prior to chloride ingress, the beams were already cracked under the load, with the RAC beams showing more transversal cracks but with a smaller width than NAC. After 10 months of combined sustained loading and chloride ingress, it was observed that the transverse cracks propagated, and a greater number of longitudinal cracks due to corrosion appeared with increasing RA content. By maintaining the load and removing the supply of chlorides, increases in the opening of transverse cracks and in the propagation of longitudinal cracks due to the accumulated chlorides within the concrete were noted. This seems to indicate that this ability of RAC to bind more chlorides and delay the appearance of surface cracks (when not previously cracked by loading) could increase the chloride threshold content.

It is possible to note a certain variability in the results obtained from the literature, which can be attributed to the different test methods, the quality of the concrete from which the RA originated or the crushing process of the RA. In practical terms, RAs that are physically and/or economically available may not be of sufficient quality to ensure durability. Bai et al. [102] showed that improving the quality of RAs can be achieved not only by removing attached mortar but also by using simpler and cheaper methods, such as reductions in w/c or modifications in the mixing process.

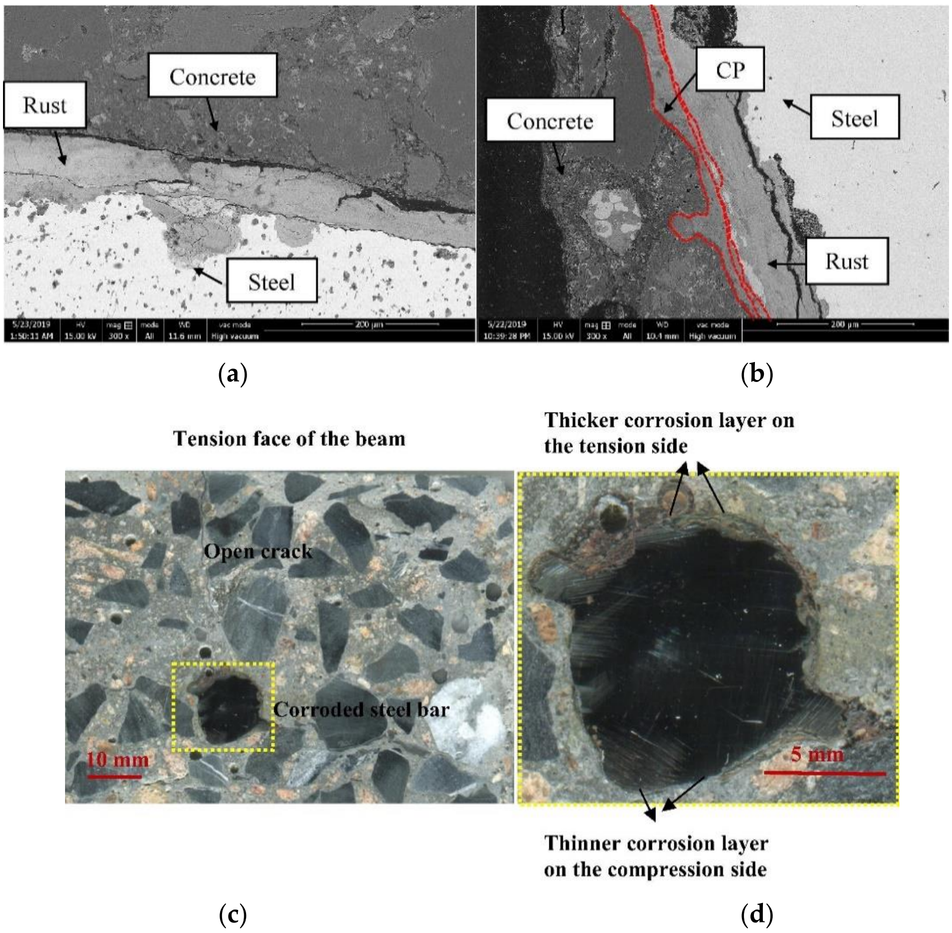


Figure 6. Images showing CP in NAC (**a**) and RAC (**b**) (reproduced from [97]) and in RAC under load (**c**,**d**). Reproduced with permission from Ref. [98]. 2019, Elsevier.

7. Conclusions

The impact of recycled aggregate (RA) on the durability of reinforced concrete against corrosion has been extensively investigated, but the issue has not yet been fully elucidated. RA increases the porosity of concrete cover, and this is generally considered a sufficient reason to classify this aggregate as detrimental, but the effect is more complex, and there are some additional aspects that need to be considered. The present literature review addresses both the initiation phase (carbonation and chloride ingress) and propagation phase (electrical resistivity and cracking). Based on this, the following highlights emerge:

- While the attached mortar leads to an overall increase in the pore connectivity of the concrete, this effect may be compensated by an improvement in the interfacial transition zone due to the dynamic process of particle absorption during mixing. This aspect is suggested by the results of RAC resistivity and the associated formation factor. The resistivity of saturated concrete decreases with the RA content as a function of the increase in total porosity. However, in unsaturated concrete, the relative increase is less significant because RAC and NAC (with the same w/b) hygroscopically achieve a similar pore fluid content. Furthermore, the matrix formation factor generated in RAC is relatively improved compared to concretes with non-porous aggregates when aggregates are incorporated in dry conditions during the mixing. The suggested improvement in the interfacial transition zone and the connectivity of the matrix itself are interesting aspects for further investigation. Bridging this knowledge gap will allow quantification of the extent to which the pore network is affected by the saturation degree of RAs when they are incorporated into the mix.

- The attached mortar in the RA may provide an additional reserve of carbonatable hydration products, increasing the carbon binding capacity of RAC. Carbonation leads to changes in the microstructure of the concrete, and therefore, a carbonation treatment has the potential to reduce the porosity of the RA prior to its use in new concrete.
- Chloride ingress in RAC is faster than in NAC (same w/b) when they are saturated, as a reflection of the total concrete porosity. However, in unsaturated concrete, the situation is less clear. Since chloride transport occurs in the pore phase containing liquid and the impact of RA on the mesoporosity is not very significant, the rate of chloride ingress in unsaturated recycled concrete does not increase significantly, unless it is concrete with a very low water/cement ratio. Moreover, the content of hydration products of the attached mortar provides additional chloride binding capacity and produces a delay in the chloride ingress process. Further research on methods to include chloride binding capacity in service life models seems valuable.
- The progression of corrosion cracking can be connected to the large amount of the interfacial transition zone in RAC. Conversely, the increased porosity of concrete containing RA can mask significant levels of deterioration without significant external symptoms. In this respect, further research needs to be carried out on the loading capacity after corrosion-induced loss of bonding in RAC elements.

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