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A review on deterioration Mechanisms, durability prediction and enhancement techniques for recycled aggregate concrete

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ABSTRACT

The expanding global construction industry is driven by the need to develop sustainable alternatives to replace natural resources in concrete manufacturing. Reusing construction materials and increasing reuse effectiveness have emerged as popular study areas. Recently, the durability of recycled aggregate concrete (RAC) has drawn attention of numerous researchers worldwide. This review paper discusses the different approaches used to predict the durability of RAC (deterministic, probabilistic, and artificial intelligence). In addition, a critical review of the parameters more influential on the RAC durability performance is presented, including replacement ratio, particle size, chemical admixtures and additives, mixing technique, and curing conditions. Several contradictory results concerning the chloride ingress, carbonation, air and water permeability in the RAC are reported and discussed. The methods used to enhance the characteristics coarse recycled aggregate (CRA) are also categorised and summarised. We have found that complex, non-linear, and multivariable mechanisms control chloride ingress, carbonation, and permeability, rendering conventional modelling techniques inadequate. It is therefore advised to use artificial intelligence methods supported by comprehensive databases to provide precise durability predictions. The performance of RAC is greatly impacted by the adhered mortar (AM) in CRA; its increased porosity and water absorption result in weaker interfacial transition zones (ITZs), decreasing impermeability, and weakening resistance to carbonation and chloride ingress. Therefore, we have also reported that strengthening the microstructure or altering AM characteristics are the main treatment strategies used to increase RAC durability performance. By enhancing RAC performance and lowering the ecological footprint of construction and demolition waste, CRA carbonation stands out among these techniques as a potential technology that offers both technical and environmental benefits.

1. Introduction

The fast expansion of concrete production has resulted in several environmental challenges, including the exhaustion of natural resources, landfill overcrowding, and CO_2 emissions (Xiao et al., 2012; Lafayette et al., 2018; Asgari et al., 2017). Using construction and demolition wastes (CDW) as recycled aggregates (RA) is a solution for decreasing the natural aggregate consumption for concrete manufacturing in addition to minimising these wastes (Poon and Chan, 2007; Etxeberria et al., 2007). In 2020, CDW was classified as the main mineral waste, accounting for 37.5 % of total waste in Europe (Statistics | Eurostat, 2024). In 2023, Europe's CDW reached 450–500 million tons, China generated about 3500 million tons while between 2022 and 2026, the US is expected to produce 330 million tons of CDW annually (Wu et al., 2024).

Although there have been many numerical and experimental studies on recycled aggregate concrete (RAC) over the last 40 years (Garcia-Troncoso et al., 2021; Kurad et al., 2017), the application of RA is

Abbreviations: AM, Adhered Mortar; BFS, Blast Furnace Slag; CRA, Coarse Recycled Aggregate; CDW, Construction and Demolition Waste; FA, Fly Ash; ITZs, Interfacial Transition Zones; LCA, Life Cycle Assessment; MK, Metakaolin; NAC, Natural Aggregate Concrete; OPI, Oxygen Permeability Index; RA, Recycled Aggregate; RAC, Recycled Aggregate Concrete; SCMs, Supplementary Cementitious Materials; SF, Silica Fume; W/C, Water-to-Cement Ratio; WA, Water Absorption.

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presently restricted due to a restrictive normative context and inadequate understanding of the performance of RAC (Kazmi et al., 2021; Wang et al., 2024). While studies concentrated on RAC's mechanical features (Akbarnezhad et al., 2013; Munir et al., 2020; Yu et al., 2021; Yu et al., 2024), the presence of RA significantly impacts the durability of RAC; this is why the future EN 206 standard will be based on a performance approach rather than a prescriptive one (Ma et al., 2020; Zhu et al., 2020; Mikhailenko et al., 2021). Because of the attached mortar on the RA, several studies highlight that RAC's mechanical performance is typically lower than natural aggregate concrete (NAC) (Velardo et al., 2022; Zhang et al., 2024). Detailed analyses of the mechanical characteristics have been realised, and results suggest that the drop in hardened performance of RAC is primarily connected to high water absorption (WA) and interfacial transition zones (ITZs) around the adhered mortar (AM) (Kim, 2022; McNeil and Kang, 2013; Wang et al., 2021).

Presently, the durability of RAC is being thoroughly researched. The findings demonstrate that using a higher amount of RA decreases durability performance (Guo et al., 2018; Bu et al., 2022). The durability of RAC is also a concern when considering chloride ingress, carbonation, and permeability (Abbas et al., 2009). The RAC's microstructure is represented by several ITZs that facilitate attack by aggressive agents (Kou and Poon, 2012; Xuan et al., 2017). In addition, damage can be caused by exterior environmental factors and concrete components such as the AM of RA. The studies on durability properties of RAC reveal inconsistencies in their findings because CRA is derived from different types of concrete (Thomas et al., 2013).

While some researchers claim that adding RA reduces RAC's durability (Silva et al., 2018), others argue that using RA made from high-strength concrete improves durability of RAC (Matias et al., 2014). Sabbrojjaman et al. (Sabbrojjaman et al., 2024) recently presented a literature review on incorporating glass, ceramic, and rubber wastes into concrete as fine aggregates. The study showed that glass and ceramic waste improved concrete's mechanical performance and durability compared with rubber waste, which had unstable properties. Concerning chloride ingress modelling, Jin et al. (Jin et al., 2021) studied chloride penetration into RAC, considering it a multi-phase material with seven solid phases: aggregate, old and new mortar, old and new ITZs, cracked and damaged zone. The study showed that the crack length and damaged zone have significantly impacted the transfer of aggressive agents in RAC. In this sense, researchers (Ying et al., 2013; Hu et al., 2018) developed a multi-ion transport model in RAC, considering five phases of RAC. Their numerical results highlighted that RAC's chloride diffusion coefficient (D_{eff}) strongly correlated with AM content, replacement ratio, and ITZ thickness.

According to the work cited above, the complexity of RAC's microstructure and its multi-phase nature have led to contradictory conclusions in the literature on the durability and behaviour of these concretes in their environment. Since few studies summarise experimental and numerical studies about durability of RAC between 2010 and 2024 (Guo et al., 2018; Silva et al., 2018; Tam et al., 2021; Tam et al., 2020; Liang et al., 2020), a detailed state of the art of recent work in this field with a comparative and critical review is required to clarify how RA affect the durability of RAC vis-a-vis environmental aggressions and to discuss the existing numerical models available for durability prediction. Consequently, the aims of a comprehensive review are:

(i) to conduct a review on the numerical models that serve to predict the RAC durability properties as well as lifetime assessment of RAC structures (Section 2);
(ii) to examine studies focusing on three main aspects that determine the durability performance of RAC: water and air permeability, chloride permeability, and carbonation resistance (Section 3);
(iii) to provide an overview of the existing methods to enhance the characteristics of CRA (Section 4).

Fig. 1 presents a schematic diagram of the review method and the manuscript's structure. Scopus, Science Direct and Google scholar were the main databases used to find the studies included in this review. This review examined the prevalence of common terms associated with the durability of RAC, including carbonation, chloride ingress, air and water permeability, and RAC. We collected approximately 150 Scopus indexed articles, including about 40 papers about modelling approaches to predict RAC's durability, 60 papers about experimental studies on RAC's durability, and 50 papers about current techniques to improve CRA's properties. On the basis of the main topics covered, this review provides a systematic analysis of RAC durability, including prediction models, influencing factors on durability properties, and treatment techniques of CRA. Consequently, section 2 presents a comprehensive analysis of numerical models for predicting RAC durability. Section 3 examines experimental evidence regarding three critical durability parameters: permeability, chloride ingress, and carbonation resistance. Section 4 builds upon these findings to explore practical solutions, discussing various methods and techniques for enhancing recycled aggregate properties. This structured approach allows for a thorough examination of both the fundamental mechanisms affecting RAC durability and the practical methods for improving its performance in real-world applications. The main discussions and recommendations are provided in section 5 and the conclusions in section 6.

2. Modelling approaches to predict RAC durability

2.1. Chloride ingress modelling in RAC

Over the years, mathematical models have been used to predict chloride ingress and corrosion initiation in RAC (Kyu Shin et al., 2022; Cherif et al., 2022). The accuracy of such models is determined mainly by the mechanisms and parameters considered. Table 1 summarises the research studies dealing with chloride ingress in RAC. Researchers (Ying et al., 2013; Jin et al., 2021; Xiao et al., 2012) described RAC as a five-phase material, including ITZs, and mortar, based on current models for estimating chloride ingress in RAC. Recent theoretical calculations as finite element method (FEM) considers the multi-phase approach to calculate the D_{eff} of RAC. Simulations highlighted that the D_{eff} increases as the CRA content and AM ratio rises. Conversely, the literature presents unexpected findings, indicating that the diffusion coefficient decreases as the incorporation of RA into the concrete increases (Ying et al., 2013; Jin et al., 2021; Xiao et al., 2012). To assess the impacts of CRA on chloride distribution, Ying *et al.* (Ying et al., 2013) proposed a model in which D_{eff} of each type of RAC is measured using a chloride migration test. The results showed that the D_{eff} typically rises as the CRA content increases. With an ideal five-phase model of RAC, Wu *et al.* (Wu and Xiao, 2018) devised a multiscale digital-image-driven stochastic technique to assess the impact of micro-scale unpredictability on mesoscale chloride diffusion. The suggested multiscale digital image guided randomised finite element approach effectively investigated chloride ion diffusion in RAC. Hu *et al.* (Hu et al., 2018) also employed a five-phase model to conduct numerical research on chloride diffusion. According to the findings, the effective diffusion coefficient varies in connection to high-quality AM, the ratio of AM, thinner ITZs, and substantially more excellent chloride resistance of ITZs. Using the mesoscale FEM, Yu *et al.* (Yu and Lin, 2020) studied the most frequent parameters influencing chloride diffusion in RAC. A genetic programming method established an explicit expression for linking the effective chloride diffusion coefficient with the identified essential parameters. These are CRA's shape and volume, old to new mortar's strength, and ITZ bonding characteristics. The results presented that the D_{eff} increases with high water-cement ratio (W/C), AM content, replacement ratio. Also, the results revealed that genetic programming could precisely forecast all these trends and is highly useful for analysing the chloride diffusion characteristics.

Dehvari *et al.* (Dehvari et al., 2021) analysed probabilistic service life

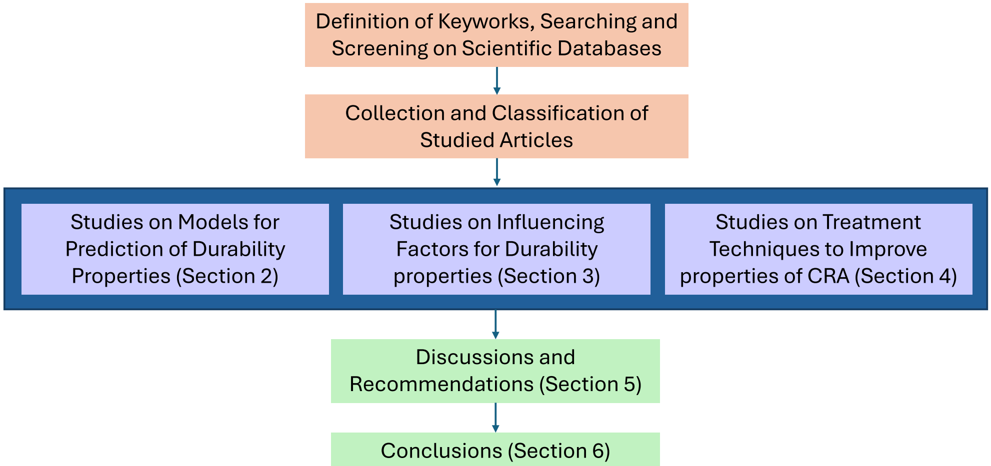

Fig. 1. Schematic diagram of the review method and manuscript's structure.

in chloride-contaminated RAC structures. The prediction models were developed using a neural network, followed by a new approach to probability evaluation that is simple and quick to use. The results show that t_{ini} is around 22 years for an aggregates ratio of 50:50, and a chloride-contaminated percentage of 5 %. Ying et al. (Ying et al., 2016) applied a probabilistic knowledge to forecast the probability distribution of D_{eff} impacted by AM in RAC. The probability distribution of D_{eff} was generated from the probability distribution of the attached mortar rate (R_{rm}) and D_{eff} of old AM ($D_{eff,\ om}$). It was found that the coefficient of variation of D_{eff} differs from that of R_{rm} and $D_{eff,\ om}$. The development, verification, and application of a 1D chloride diffusion modelling and service life in reinforced RAC were described by Stambaugh *et al.* (Stambaugh et al., 2018). The findings also suggested that RAC with SCMs could be employed in applications with long-term chloride exposure.

The durability of RAC formulations containing other additions was investigated through numerical and experimental techniques. Singh *et al.* (Singh et al., 2022) employed a mathematical model to predict chloride diffusion in RAC containing metakaolin. The models have been exact and account for data correlation based on experimental results. Amiri and Hatami (Amiri and Hatami, 2022) used artificial neuron networks (ANN) to forecast chloride migration in RAC-containing blast furnace slag (BFS). The results demonstrated that CRA increases the chloride migration ratio. Except in the early phases, slag reduces the adverse effects of CRA by improving hydration products. Xiao *et al.* (Xiao et al., 2014) used Fick's law to predict chloride distribution for various immersion times and CRA replacement levels. Their results showed that changes in the replacement ratio of CRA significantly impacted the free chloride concentration as immersion time increased. In contrast, the rate of free chloride concentration with a 100 % replacement ratio is more significant than that of NAC.

2.2. Carbonation modelling in RAC

Table 2 summarises studies dealing with the carbonation of RAC. Silva *et al.* (Silva et al., 2016) applied a multivariate regression algorithm to predict the carbonation rate, considering mix design features, ambient conditions, and the properties of CRA as input parameters. The findings show many parameters that affect the carbonation rate, such as compressive strength, clinker content, CO_2 concentration in the atmosphere, and CRA's water absorption (WA). A correlation between the model and experiment was shown by the R^2 of 0.792 (and an adjusted R^2 of 0.791) that was achieved. Additionally, the result indicates that the variables under consideration may account for 79.2 % of the variability of the carbonation rate. Carevic *et al.* (Carević et al., 2019) examined how to predict the carbonation depth described by the 2010 fib Model Code. It was demonstrated that NAC and RAC may use the current models, which provide the link between natural and accelerated carbonation depth. Meanwhile, Zhang *et al.* (Zhang and Xiao, 2018) improved existing prediction models by introducing the weighed aggregate's WA. This model is more effective than the simplified *fib*, Xiao Lei model. The CoV in the model decreased by 33.3 % compared to the CoV decrease of 55.2 % when the Lei's model is used (Lee and Wang, 2008), and a decrease of 16.2 % when the Silva's model is used. (Silva et al., 2016). A carbonation experiment conducted ten years ago validates the suggested model, demonstrating its reasonableness and suitability for predicting the carbonation depth.

Liu *et al.* (Liu et al., 2021) used ANNs combined with swarm intelligence systems to estimate carbonation depth. The input parameters were W/C, replacement ratio, WA, temperature, RH, CO_2 concentration, age and exposure period. The results revealed that ANN combined with swarm intelligence performed better than single models. Moreover, Nunez *et al.* (Nunez and Nehdi, 2021) have suggested a tree model to estimate the carbonation depth using several SCMs. The developed carbonation depth model was proved by indexing with varied random seeds, resulting in a root mean square error of 1.5, an absolute error of 0.948, and an R^2 of 0.97.

2.3. Water permeability modelling in RAC

Few studies have predicted water permeability in RAC. Chen *et al.* (Chen et al., 2020) proposed a back-propagation neural network to analyse permeability features. This study utilised a unilateral and a bilateral model to calculate the permeability coefficient of RAC. The Mean Relative Error (MRE) and Mean Absolute Error (MAE) of water permeability in the two models were 6.26 % and 0.27 mm/s, 4.25 % and 0.18 mm/s, respectively, which proved that the two prediction models have high accuracy.

3. Experimental studies to investigate the durability of RAC

3.1. Investigations on chloride ingress into RAC

Table 3 summarises the main factors influencing the chloride ingress into RAC: (1) CRA replacement ratio, (2) CRA's properties, (3) Supplementary cementitious materials (SCMs), (4) W/C ratio, and (5) curing duration. CRA replacement rates are the primary factor affecting chloride ingress into RAC (Ma et al., 2019). It is worth noting that the D_{eff} rises in lockstep with the amount of CRA. The D_{eff} of RAC is approximately 1.5 times higher compared to NAC. Guo *et al.* (Guo et al., 2018) concluded in a review study that during a standard chloride migration test, the charge passed rises as replacement ratio increases (Fig. 2). This

Table 1
Summary of models dealing with chloride ingress in RAC.

Application	Input parameters	Results	Ref.
Calculate chloride diffusion coefficient (D_{eff}) using ANN modelling.	Five-phase material, including ITZs, mortar, and aggregate	D_{eff} reduces as the CRA content increases but increases with the AM rate and the ITZ depth.	(Ying et al., 2013; Jin et al., 2021; Xiao et al., 2012; Liu et al., 2015; Liu et al., 2022; Liu et al., 2023; Liu et al., 2023; Shen et al., 2019)
Probability distribution of chloride concentration	Aggregate particles distribution	Chloride diffusivities rise as the CRA content increases, and R^2 = 1 indicates that the highly relevant data are credible.	(Ying et al., 2013)
Calculate the coefficient of variation (CoV) of chloride diffusivity	Micro-scale randomness	The CRA shape, the new ITZ's thickness, and the recycled aggregate's size considerably affect the CoV in chloride diffusivity in the RAC model.	(Wu and Xiao, 2018)
Predict chloride diffusion coefficient.	The shape of CRA, the volume of RA, the strength of mortar, and the bonding characteristic of ITZs	The D_{eff} increases with W/C, AM content, and replacement ratio growth.	(Yu and Lin, 2020)
Predict chloride concentration distribution.	Immersion times and CRA replacement	At a specific immersion period, the difference between the free Cl^- concentration with a replacement ratio of 100 % and 0 % increases first as depth increases and eventually decreases.	(Xiao et al., 2014)
Analysis of probabilistic service life in chloride-penetrated RAC	W/C and silica fume content	At W/C = 0.4, SF = 10 %, RH = 70 %, t = 23 °C, and pre-contamination percentage of 5 %, the time to initial corrosion is around t_i = 22 years with reliability index of 3.0	(Dehvari et al., 2021)
Predict chloride ion penetration.	Metakaolin content	Models have been developed with high precision and data correlation based on experimental results.	(Singh et al., 2022)
Predict chloride migration	Slag content, CRA content	R^2 = 0.9912 proves that using high-content CRA increases the chloride migration ratio, and slag reduces the adverse effects of CRA by improving hydration products.	(Amiri and Hatami, 2022)
Predict probability distribution of D_{eff}	AM rate	CoV of $D_{eff, RAC}$ of 0.136, which is different from that of R_{rm} and D_{om}.	(Ying et al., 2016)
1D numerical service-life prediction model	SCMs content	The most practical way to provide RAC a 50-year service life is to apply either FA or slag.	(Stambaugh et al., 2018)

Table 2
Summary of models dealing with carbonation RAC.

Application	Input parameters	Results	Ref.
Predict carbonation rate	Mix design features, ambient conditions, and the properties of CRA	R^2 = 0.792 proves a correlation between experimental and prediction model.	(Silva et al., 2016)
Predict carbonation depth	CO_2 concentration	Compared to natural conditions, the carbonation depth was 12 %, 22 %, 35 %, and 50.5 % lower for CO_2 concentrations of 1 %, 2 %, 4 %, and 16 %, respectively.	(Carević et al., 2019)
Predict carbonation depth	CO_2 concentration and weighed water absorption	The R-value decreased by 33.3 %.	(Zhang and Xiao, 2018)
Predict carbonation depth	Mix proportion and experimental parameters.	R^2 values of ANN, GPR, and RF algorithms are 0.929, 0.936, and 0.943, respectively, proving that the RF model's performance is better than that of the GPR and ANN models.	(Liu et al., 2021)
Predict carbonation depth	Pozzolanic materials content, Mix proportion parameters	The average R^2 values of the model testing are 1.5139, 0.948, and 0.9707, respectively. The R^2 for the training set was 0.0822, 0.0249, and 0.999, respectively.	(Nunez and Nehdi, 2021)

implies that the charge passed of RAC is around 2.07 times compared to NAC, with a 95 % probability. Incorporating CRA reduces resistance to chloride diffusion because applying CRA increases the pore diameter, the cracks in the ITZs, and porosity of RAC (Leng et al., 2000; Wu and Xiao, 2018). Indeed, due to the characteristics of AM and ITZs, the high permeability of CRA rises chloride penetration into RAC (Xu et al., 2021; Hu et al., 2022).

CRA's properties are related to RA production from parent concrete (Shaban et al., 2019; Katz, 2003; Katz, 2004). Ma *et al.* (Ma et al., 2019) reported that the D_{eff} in 100 % RA design is about 1.67 times compared to NAC. Duan *et al.* (Duan and Poon, 2014) studied three types of CRA to investigate impact of AM content on Cl^- penetration of RAC: CRA1 contains crushed concrete and excavated rock; CRA2′s composition includes masonry wasted besides concrete; CRA3 consists of recycled concrete aggregate. The most adherent mortar was found in CRA3, followed by CRA2 and CRA1. The outcomes indicate that the Cl^- resistance of RAC produced with RAs was generally lower and deteriorated along the following trend: CRA1 > CRA2 > CRA3 (Fig. 3). At 28 and 90 days, the chloride resistance with CRA1 was comparable to NA. These phenomena indicate that the AM content significantly impacts Cl^- penetration resistance. The chloride resistance of the tested concretes made with RA decreases as the attached mortar content increases for all the concrete classes (C30, C45 and C60). Moreover, Kou *et al.* (Kou and Poon, 2015) used crushing parent concrete to the size of 20 mm and then used it to generate normal strength and high-performance RAC. The chloride ingress into mixtures made with CRA generated from higher-strength concrete was less than that of normal-strength concrete.

Table 3
Summary of the main factors influencing RAC chloride ingress.

Influencing factors	Comments	Curing duration	Chloride ingress results	Ref.
CRA replacement ratio	100 %	28 days	The D_{eff} of RAC is 1.5 times that of NAC.	(Ma et al., 2019)
	100 %	28 days	The total charge passed by RAC is 2.07 times that of NAC	(Guo et al., 2018)
CRA's properties	WA of CRA = 6 % and WA of CRA = 0.5 %	28 days	The D_{eff} of RAC with WA = 6 % is 1.67 times larger than RAC with WA = 0.5 %	(Ma et al., 2019)
	Composition of coarse recycled aggregate	28 days	Total charge passed values of RAC1, RAC2, and RAC3 are about 5200, 5300, and 8000 C, respectively, with target strength C30.	(Duan and Poon, 2014)
		90 days	Total charge passed values of RAC1, RAC2, and RAC3 are about 3600, 4900, and 6000 C, respectively, with target strength C30.	(Duan and Poon, 2014)
	CRA from C30, C45, C60, C80, C100 parent concrete (W/C = 0.35)	28 days	Total charge passed values of RAC30, RAC45, Rac60, RAC80, and RAC100 are about 2600, 2450, 2400, 2200, and 1900 C, respectively.	(Kou and Poon, 2015)
Supplementary cementitious materials (SCMs)	100 % CRA	Ten years	RAC with 25 %, 35 %, and 55 % FA substituted cement have total charge passed values reduction by 28.1 %, 33 %, and 43.1 %, respectively, compared to RAC without FA.	(Kou and Poon, 2013)
	100 % CRA W/C = 0.40 25 % replacement ratio of SCMs	28 days	The D_{eff} of NAC and RAC with cement, FA, Slag, and SF are 3.55x10-8, 5.62x10-8, 4.5x10-8, 4.61x10-8, and 3.92×10^{-8} cm^2/s, respectively.	(Qin et al., 2010)
	100 % CRA	28 days	Total charges passed are 6587, 3521, and 3305 Coulombs for RAC, RAC with 30 % FA, and RAC with 65 % slag.	(Ann et al., 2008)
	100 % CRA	28 days	The total charges passed by RAC, RAC with 30 %FA, and RAC with 10 % SF are 6000, 1900, and 1200 Coulombs, respectively.	(Corral-Higuera et al., 2011)
	100 % CRA	28 days	Charge passed of RAC with 25 % SF reduces 60 % compared to NAC	(Sasanipour et al., 2019)
	100 % CRA	90 days	Charge passed of RAC and RAC-10SF, RAC-15MK, RAC-35FA, and RAC-55Slag are 4000, 3200, 3100, 2900, and 2800 Coulombs.	(Kou et al., 2011)
	100 % CRA	91 days	RAC-SF5 and RAC-SF10 have D_{eff} of 5.4 and 7.5×10^{-12} m^2/s, respectively, compared to 3.7×10^{-12} m^2/s for the RAC-SF0 mix.	(Pedro et al., 2017)
W/C ratio	W/C = 0.45 ÷ 0.55	35 days	The D_{eff} rises 47 % in RAC with 0 %, 20 % CRA and 127 % in mixes with 50 %, 100 % CRA	(Vázquez et al., 2014)
Curing time and temperature	W/C = 0.43 ÷ 0.45	28 days 91 days	D_{eff} values fell between 12 % and 20 % from 28 to 91 days.	(Pedro et al., 2017)
	RAC with the cement replacement ratio of 50 %, 100 % and, 25 %, 35 %, 55 % class-F FA	28 days and ten years	As the amount of FA increased, the total charge passed was reduced. The most minor charge passed in the concrete containing 55 % fly ash.	(Kou and Poon, 2013)
	W/C = 0.55 and 0.45	Water-curing and steam-curing	Chloride penetration resistance increased from 28 to 90 days. Steam curing shows better resistance.	(Poon et al., 2006)
	W/C = 0.35, 0.45, 0.55, and replacement ratio of 50 % and 100 %	28 days	RAC cured in humid surroundings had the lowest chloride migration coefficients,	(Amorim Júnior et al., 2019)

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Table 3 (*continued*)

Influencing factors	Comments	Curing duration	Chloride ingress results	Ref.
			whereas concrete cured in laboratory conditions had the greatest	

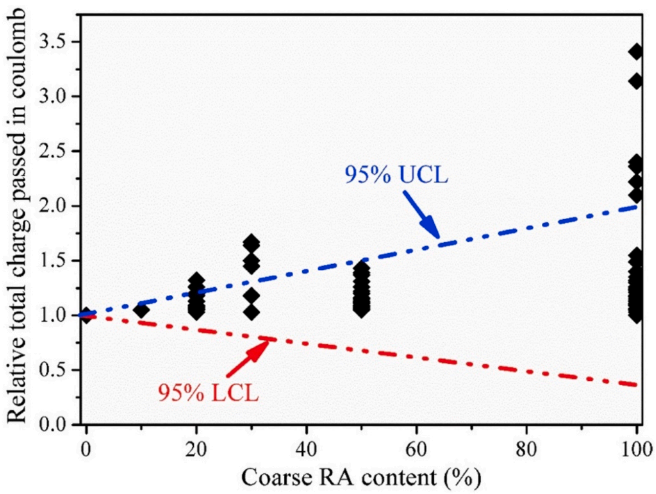

Fig. 2. Impact of CRA content on the relative total charge passed (Taken from (Guo et al., 2018). UCL: upper confidence limit, LCL: lower confidence limit.

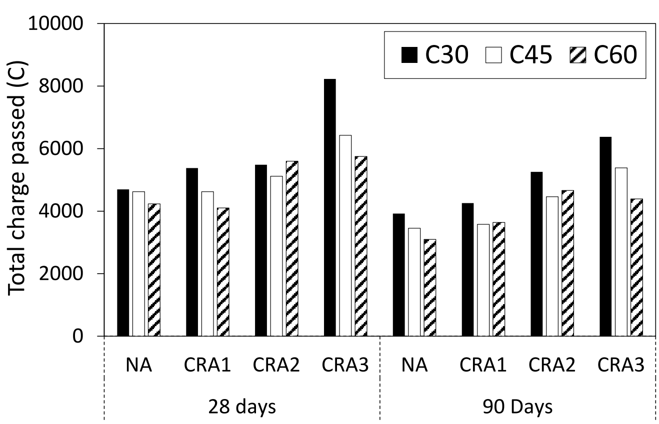

Fig. 3. Influence of various types of CRA on chloride penetration into concrete (Elaborated with data from (Duan and Poon, 2014).

Fig. 4 illustrates the interactions between pozzolanic materials with CRA as well as their effects on concrete properties. SCMs improve the filling effect, improve morphological function, and lower the cement content. By affecting chemical reactions, these effects improve performance. C-S-H which is produced as a result of the pozzolanic reaction, improves mechanical and durability properties. The cementitious matrix is further enhanced by the release of necessary ions such as Ca^{2+}, Al^{3+}, $AlOH^{2+}$and Si^{4+} by ion exchange (Somna, 2012; Kurda et al., 2017; Wu et al., 2011; Faella et al., 2016; Neville, 2011). The optimal proportion for substituting cement with fly ash (FA) in RAC is 20 %, which results in the best chloride resistance. Adding FA to RAC refines the porosity (Kurda et al., 2018), increases C-S-H content and chloride fixation capacity (Kou and Poon, 2013), and leads to the development of new ITZs (Chindaprasirt et al., 2007; Liu et al., 2020). Qin *et al.* (Qin et al., 2010) showed that 25 % FA, blast furnace slag (BFS), silica fume (SF) are

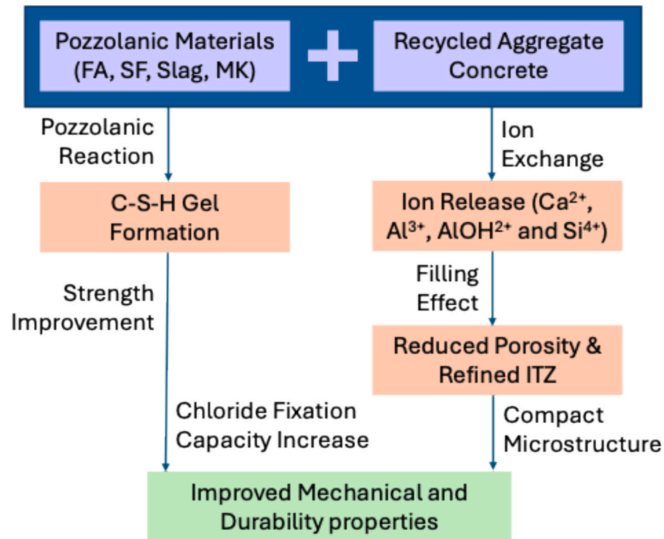

Fig. 4. The interaction of pozzolanic materials with CRA and their various effects on concrete properties.

cement substitutes in RAC, and their chloride diffusion coefficient is similar to NAC. FA, BFS, and SF reduce the pore diameter of RAC. Furthermore, the pozzolanic reaction generates C-S-H gel, which can physically adsorb more chlorides in the interlayers and diminish the diffusing channels (Chatterji and Kawamura, 1992). Additionally, the quantity of Ca^{2+}, Al^{3+}, $AlOH^{2+}$, and Si^{4+} in FA, BFS, and SF is more than that in cement, resulting in the total ion content in the mix proportion when conducted cement substitution of FA, slag, and SF in RAC increase (Neville, 2011; Cherif et al., 2020). Ann *et al.* (Ann et al., 2008) found that combining 30 % FA with 65 % slag increased the chloride resistance of RAC. Furthermore, during a chloride migration test, the charge passed in the RAC with 30 % FA or 10 % SF was discovered to be three and five times lower, respectively, than that of the reference RAC (Corral-Higuera et al., 2011). Furthermore, Sasanipour *et al.* (Sasanipour et al., 2019) concluded that SF effectively controlled chloride ingress and decreased charge passed. The replacement amount of 25 % CRA and the ratio of 8 % SF had a lesser effect on reducing RAC's Cl^- penetration resistance. As a result, adding SF as a modifying material function as a filler to close the internal pores of CRAs, leading to reduced porosity, compact microstructure, and better ITZs, but it also promotes hydration due to its high reactivity. Kou *et al.* (Kou et al., 2011) showed that replacing cement with 10 % SF or 15 % metakaolin (MK) or with 35 % FA or 55 % slag reduces the total charge passed. Meanwhile, Pedro et al. (Pedro et al., 2017) assessed commercially densified SF and CRA content effects on the properties of RAC. Three concrete groups were created, containing SF: 0 %, 5 % (RAC-SF5), and 10 % (RAC-SF10) of the binder mass. In addition, FA and superplasticiser are used in concrete mixes. The research revealed that SF incorporation has the worst outcomes. RAC-SF5 and RAC-SF10 have D_{eff} of 5.4×10^{-12} m^2/s and 7.5×10^{-12} m^2/s, respectively, compared to 3.7×10^{-12} m^2/s for the mix without SF.

Moreover, W/C affects chloride diffusion into RAC (Neville, 2011). It is related to porosity and a poor interface between cement paste and aggregates (Sasanipour et al., 2021). In a great W/C mix proportion, more chloride enters by the path of AM and several ITZs, resulting in the impacts of the CRA ratio being more important than that of low W/C of RAC (Liang et al., 2021). When the W/C > 0.40, Villagrán-Zaccardi *et al.* (Villagrán-Zaccardi et al., 2008) found that Cl^- penetration was equal for NAC and RAC; in this sense, Vázquez *et al.* (Vázquez et al., 2014) depicted that D_{eff} with the same W/C are relatively similar between NAC and RAC when CRA content is low (between 0 % and 20 %). It was also discovered that increasing W/C from 0.45 to 0.55 increases the diffusion coefficient. At 35 days, this rise is roughly 47 % in RAC with 0 %, 20 %

CRA and 127 % in mixes with 50 %, 100 % CRA.

Chloride penetration is affected by period and temperature. With increasing curing time, resistance to chloride ingress improves, and the benefit is noticeable at early ages (Bravo et al., 2018). Because the hydration process accelerates as the curing period rises, and a higher degree of hydration leads to denser ITZs, resulting in fewer voids and less chloride intrusion into the RAC, but on real structure, it is impossible to optimise the curing time (Sasanipour and Aslani, 2019). When curing from 28 to 91 days, Pedro *et al.* (Pedro et al., 2017) found that chloride diffusion coefficient values fell between 12 % and 20 % because the old mortar may contain mineral additions, as the hydration of concrete without mineral addition is supposed to be over at 28 days. In comparison, Kou *et al.* (Kou and Poon, 2013) showed that even after ten years of environmental exposure, the resistance to chlorides of RAC incorporating fly ash was still lower than that of NAC. When various curing procedures were applied to RAC, chloride ingress was different. For instance, Poon *et al.* (Poon et al., 2006) compared the resistances of water-cured and steam-cured to chloride ingress. Compared to traditional water curing, the results concluded that steam curing increased RAC's chloride resistance. After 90 days, Amorim *et al.* (Amorim et al., 2012) found that concrete cured in humid surroundings had the lowest chloride migration coefficients, whereas concrete cured in laboratory conditions had the greatest. The discrepancies revealed can only be explained by the wet curing circumstances leading to a finer microstructure because the concrete samples were pre-saturated before the screening.

3.2. Investigations on RAC carbonation

Five factors influencing the RAC carbonation are studied in this section and summarised in Table 4: (1) CRA replacement ratio, (2) curing conditions, (3) superplasticiser (SP) and mixing methods, (4) supplementary cementitious materials (SCM) and (5) W/C.

The results presented that carbonation depths with 25 %, 50 %, and 100 % CRA increased by 52 %, 63 %, and 127 %, respectively, compared to NAC, according to Pedro *et al.* (Pedro et al., 2017).

Amorim et al. (Amorim et al., 2012) showed that curing conditions affect carbonation. The findings revealed that when concrete contains 100 % CRA, the carbonation depth increased noticeably by 19 % for immersion curing, 23 % for the wet chamber, 27 % for the surrounding environment, and 30 % for laboratory curing, compared to NAC.

Carbonation resistance of RAC was enhanced by using superplasticiser (SP) and mixing approaches. Otsuki *et al.* (Otsuki et al., 2003) optimised the new ITZs using a two-fold mixing procedure, resulting in more dense ITZs and a reduction of 12.3 % in carbonation depths with W/C of 0.55. The presence of SP influenced the resistance to carbonation, particularly at the 7-day age (Matias et al., 2014). The adsorption of SP can slow down the formation of mixed crystals (C_3S, C_3A) and change their shape, causing crystals to become more assertive on the cement surface and join the cement particles in the paste.

Kou et al. (Kou and Poon, 2013) presented the cement replacement by FA in RAC increases its carbonation depth when rise of the FA content. The carbonation rate of NAC was roughly 1.68 times that of the RAC, with 55 % FA in binder mass after ten years of natural exposure to CO_2. The phenomenon is due mainly to decreased porlandite content because of the pozzolanic reaction (Khunthongkeaw et al., 2006). Singh *et al.* (Singh and Singh, 2016) concluded that increasing FA content of RAC increased carbonation depths for all exposure times and curing ages. Furthermore, the vastly improved dense microstructure in RAC caused by adding MK was also a significant reason for the lowered carbonation depths compared to that of NAC. Whereas, regarding the influence of the SF, Pedro et al. (Pedro et al., 2018) conducted a study to assess the impact of incorporating silica fume (SF) and recycled aggregates (RA) on the carbonation coefficient of concrete. Three categories of concrete were examined: (i) reference concrete RC without SF and RA; (ii) C100FRA100CRA with 100 % fine recycled aggregates and 100 % Coarse recycled aggregates; (iii) C100C with 100 % coarse recycled aggregates. Within each category, three concrete mixes were prepared with varying cement replacement levels by SF: 0 %, 5 % and 10 %. The findings showed that the concretes with 0 %, 5 % and 10 % SF exhibited carbonation coefficients ranging from of 0.85 to 1.36 mm/(year)$^{0.5}$; 0.61

Table 4
Summary of the main factors influencing RAC carbonation.

Influencing factors	Comments	Curing duration	Carbonation related results	Ref.
CRA replacement ratio	25 %, 50 %, 100 % replacement ratio	28 days	Carbonation rate with 25 %, 50 %, and 100 % CRA rose by 52 %, 63 %, and 127 %, respectively, compared to NAC	(Pedro et al., 2017)
Curing conditions	100 % CRA	28 days	Carbonation depth increases by 19 % for immersion, 23 % for the wet chamber, 27 % for the surrounding environment, and 30 % for laboratory curing, compared to NAC.	(Amorim et al., 2012)
Superplasticiser (SP) and mixing methods	100 % CRA W/C = 0.25 use method follows JIS A1138, W/C = 0.4, 0.55, 0.7 use double mixing method	28 days	Carbonation depths of RAC and NAC are 0.1 and 0.25 with W/C = 0.25, 5, and 2.5 with W/C = 0.4, 12.5, and 7.5 with W/C = 0.55, 19, and 17.5 with W/C = 0.7, respectively.	(Otsuki et al., 2003)
	100 % CRASP1 (standard superplasticiser) SP2 (high-performance superplasticiser)	91 days	Carbonation depths of RAC with SP1 are higher than that of RAC with SP2 and reference RAC.	(Matias et al., 2014)
Supplementary cementitious materials (SCMs)	FA replacement level of 55 %	10 years	The carbonation rate of NAC is 1.68 times that of RAC with 55 % FA.	(Kou and Poon, 2013)
	100 % CRA	28 days	RAC with 0 %, 5 %, and 10 % SF have carbonation rates of 0.85 to 1.36 mm/(year)$^{0.5}$; 0.61 to 1.18 mm/(year)$^{0.5}$ and 0.51 to 0.90 mm/(year)$^{0.5}$, respectively.	(Pedro et al., 2018)
W/C	W/C = 0.25, 0.4, 0.55, 0.7		Carbonation depths of RAC increased with increasing W/C ratio	(Otsuki et al., 2003)

to 1.18 mm/(year)$^{0.5}$ and 0.51 to 0.90 mm/(year)$^{0.5}$, respectively (Fig. 5). The carbonation coefficient decreased with increasing SF content across all concrete categories, particularly for the C100FRA100CRA group, which initially had a higher carbonation coefficient. The effect of SF in the other two categories was less pronounced, as these concretes already demonstrated a high resistance to carbonation without SF. The observed reductions in carbonation with SF incorporation are attributed to the formation of hydration products that refine the concrete's microstructure, despite a reduction in portlandite content due to the pozzolanic reaction. These hydration products also enhance the CO_2 fixing capacity of the material (Pedro et al., 2018). Torgal *et al.* (Pacheco Torgal et al., 2012) concluded that RAC samples lacking SCMs had the least carbonation, followed by samples containing slag and FA.

Few studies regarding the impact of W/C on RAC's carbonation depth are contradictory. For example, increased carbonation depths of RAC were observed by increasing the W/C ratio (Bu et al., 2022; Otsuki et al., 2003). Finally, when CRA was generated using a two-stage impact crusher, Pedro et al. (Pedro et al., 2014) concluded the carbonation rate was lower than when using only an impact crusher. The decreased AM content stored after the two-stage grinding process could be the reason for various strength levels. Due to the increased porosity of CRA, RAC's carbonation was slightly faster than NAC's.

3.3. *Investigations on water permeability, water absorption (WA), and air permeability*

Table 5 summarises the main factors discussed in the literature that influence RAC's water permeability, water absorption (WA), and air permeability: (1) CRA replacement ratio, (2) W/C ratio, (3) Source of CRA, (4) Curing age, (5) Mineral additive. The water permeability, water absorption (WA), and air permeability of RAC increase as W/C rises at a given coarse recycled aggregates (CRA) ratio (Thomas et al., 2013; Levy and Helene, 2004). Moreover, when using superplasticiser (SP), the WA of RAC reduces since less water to achieve the desired workability, leading to a drop in porosity (Kou and Poon, 2012; Kou and Poon, 2013).

The WA of RAC with 100 % CRA by immersion and capillarity rose 26.9 % and 41.7 %, respectively (Soares et al., 2014). The increased WA is due to the CRA's great water content (Olorunsogo and Padayachee, 2002). Similarly, increased CRA replacement was associated with higher oxygen permeability of RAC as measured by the oxygen permeability index (OPI) for a given W/C and age. Olorunsogo et al. (Olorunsogo and Padayachee, 2002) presented that the OPI for RAC containing 50 % and 100 % CRA were 37.6 % and 38.2 %, respectively.

The penetration depth, OPI, and WA increase as the W/C increases at a given CRA ratio (Bravo et al., 2018). Moreover, when using superplasticiser (SP), the WA of RAC reduces since little water is needed to achieve desired workability, leading to a drop in porosity (Matias et al., 2014). Thomas et al. (Thomas et al., 2013) show that with W/C of 0.4,

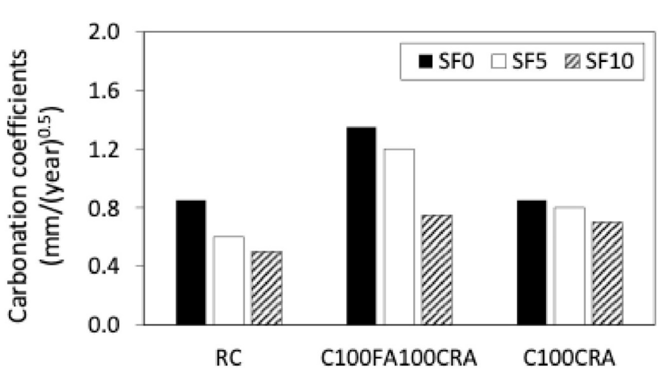

Fig. 5. Effect of SF content on the carbonation coefficients of RAC (Elaborated with data from (Pedro et al., 2018).

the OPI of NAC and RAC is approximately 2 × 10^{-17} m^2 at 28 days of age, and it rapidly evolves to 2 × 10^{-18} m^2 by 365 days of age. On the other hand, comparable results are noted for high W/C from 28 to 180 days.

The impermeability is affected by its source and crushing method due to various composition and physical properties of CRA, including shape and WA (Bravo et al., 2015). For example, RAC containing 100 % CRA from Ambilei (Portugal) increased water uptake by immersing by 22.8 %, whereas mixes containing 100 % CRA from Valnor (Portugal) increased it by 52.9 % (Bravo et al., 2015). Furthermore, total replacement of CRA increased capillary water absorption by 11.8 to 44.6 %, owing to changes in the composition of these CRA in the CRA varied between 4.2 and 28.6 % (Bravo et al., 2015).

The density of RAC rises as the curing age increases, but its air and water permeability and water absorption decrease (Olorunsogo and Padayachee, 2002; Kurda et al., 2019; Zaharieva et al., 2003; Kapoor et al., 2016). For example, the air permeability of RAC was roughly 2 × 10^{-7} m^2 after 28 days, then decreased to 2 × 10^{-18} m^2 at 365 days (Thomas et al., 2013). The OPI reduces from 16 % to 10 % for 7 and 56 days (Olorunsogo and Padayachee, 2002). The equivalent increments in WA for the same previous mixtures also decreased with the curing age: 43.6 %, 38.5 %, and 28.8 % for RAC cued for 7, 28, and 56 days, respectively (Olorunsogo and Padayachee, 2002).

The application of pozzolanic materials affects the permeability of RAC. Pozzolanic materials act as fillers, lower pore diameters, and micro-cracking in the ITZs (Neville, 2011). For instance, using FA as a partial or complete cement replacement reduced RAC's water absorption (Felix et al., 2021). The pozzolanic effects of FA were related to the more considerable decrease in water absorption for RAC mixtures. Furthermore, the WA dropped when the water-to-binder ratio decreased. More specifically, WA by immersion at 28 days was reduced by 3 % and 15 %, respectively, for the mass replacement of cement by 30 % and 60 % FA. Furthermore, when cement was substituted with FA at any age, the capillary uptake of RAC decreased (Kurda et al., 2017). Blast furnace slag improved RAC properties more effectively than FA (Henry et al., 2011). Likewise, introducing ultra-fine ingredients of SF and/or MK improves the water permeability of RAC (Kapoor et al., 2016; Çakır, 2014; Alexandridou et al., 2018).

4. Methods to improve characteristic of coarse recycled aggregate

The research above highlighted that RAC durability is widely dependent on CRA properties. Consequently, this section focuses on a review of various studies that proposed methods to improve CRA properties. CRA (mainly from recycled concrete) is subjected to treatment processes that improve their microstructure and durability (Tam et al., 2020; Ma et al., 2019). Eliminating and enhancing the quality of the adhered mortar are two critical approaches presented and discussed in this section because they have been developed over the years to strengthen the durability of RAC. Fig. 6 depicts various methods for treating CRA. Most of these methods are commonly tested in the laboratory, and their environmental impact has not been yet assessed.

4.1. *Eliminating the adhered mortar of CRA*

Table 6 summarises methods to remove AM in CRA. Mechanical milling, selective thermal grinding, and heat crushing are the most common mechanical procedures (Ouyang et al., 2020). Fig. 7 presents the reduction in the water absorption and adhered mortar content of CRA when using mechanical, thermal–mechanical and chemical–mechanical treatment methods. Mechanical treatment is the most effective method as it removes up to 62 % of the AM content, resulting in a 50 % reduction in CRA water absorption.

Dimitriou *et al.* (Dimitriou et al., 2018) applied a ball-crushing technique to minimise the volume of AM, resulting in significantly good characteristics with stronger and sounder CRA. The treatment

Table 5
Summary of the main factors influencing water and air permeability of RAC.

Influencing factors	Values	Curing duration	Results	Ref.
CRA replacement ratio	25 %	28 days	WA by immersion increases by 9.1 %, and WA by capillarity increases by 10.9 %, compared to concrete without CRA.	(Soares et al., 2014)
	100 %	28 days	WA by immersion increases by 26.9 %, and WA by capillarity increases by 41.7 %, compared to concrete without CRA.	(Soares et al., 2014)
	50 % and 100 %	28 days	Oxygen permeability index (OPI) was 37.6 % and 38.2 %, respectively.	(Olorunsogo and Padayachee, 2002)
W/C ratio	0.4 (100 % of CRA)	28 days and 365 days	Oxygen permeability is around 2x10^{-17} m^2 and 2x10^{-18} m^2.	(Thomas et al., 2013)
	>0.4 (100 % of CRA)	28 days and 180 days	No effect of W/C on Oxygen permeability	(Thomas et al., 2013)
Source of CRA	From Ambilei or Valnor zones in Portugal (100 % of CRA)	28 days	WA by immersion of CRA from Ambilei (Portugal) increases by 22.8 %, while CRA from Valnor (Portugal) increases by 52.9 %.	(Bravo et al., 2015)
	From Ambilei or Valnor zones in Portugal (10 % of CRA)	28 days	Capillary WA with 10 % of CRA from Valnor increases by 3.3 %, while that of CRA from Europontal (Portugal) increases by 0.3 %.	(Bravo et al., 2015)
Curing age	100 % of CRA	7, 28,56 days	OPI values are 16 %, 10 %, and 10 % at seven days, 28 days, and 56 days.	(Olorunsogo and Padayachee, 2002)
Mineral additives	Mass replacement of cement is 30 % and 60 %	28 days	− WA values reduce by 3 % and 15 %, respectively	(Kurda et al., 2017)

Fig. 6. Treatment techniques for improving properties of CRA.

reduced the total quantity of attached mortar in concrete by 62 % and slightly rounder aggregates, but it required much power, frequently resulting in interior damage to CRA (Shi et al., 2016). The results (Dimitriou et al., 2018) showed D_{eff} with treated CRA was noticeably lower than that of RAC without treated CRA or NAC (with NA). Microwave-assisted CRA purification technology was researched by Akbarnezhad *et al.* (Akbarnezhad et al., 2011). Microwave irradiation of air-dried CRA particle decreases resulted in a 32 % mortar content, a 19 % decrease in WA, and a 2.5 % rise in CRA density.

While previous approaches can reduce the adhered mortar's water absorption and content, they still have certain drawbacks, such as high energy requirements, bulky equipment, sophisticated methods, and machinery wear (Ma et al., 2019). Tam *et al.* (Tam et al., 2007) used pre-soaking chemical cleaning methods to reduce the mortar adhered to CRA, including $ReMortar_{HCl}$ (pre-soaking with HCl), $ReMortar_{H2SO4}$ (pre-soaking with H_2SO_4), and $ReMortar_{H3PO4}$ (pre-soaking with H_3PO_4) as shown in Table 6 (chemical treatment). The results depicted that the WA was dramatically lowered after the pre-treatments, with improvements ranging from 7.27 % to 12.17 %. Kim *et al.* (Kim et al., 2018) investigated two distinct methodologies with HCl or Na_2SO_4 pre-treatment while remaining aggregate-to-solution ratio constant at 1.0:4.5. Both pre-treatments produced concretes that performed better regarding carbonation and chloride resistance.

Furthermore, Purushothaman *et al.* (Purushothaman et al., 2015) compared chemical and mechanical treatment techniques affecting the AM properties. NCA, CRA, CRA treated with acid, and CRA obtained after cleaning processing, heating, and cleaning treatment are used to make six different concrete compositions. The results revealed that pre-soaking CRA (without limestone aggregate) in H_2SO_4 removes the adhering mortar of CRA more effectively than HCl. Heating and cleaning appear to increase quality of CRA and, thus, the property of RAC in mechanical treatment procedures. Kazmi et al. (Kazmi et al., 2019; Kazmi et al., 2020) applied CH_3COOH immersion and ball-crushing to enhance properties of RAC. The treated RAC exhibits spliting tensile strengths of 93 % and flexural strengths of 94 % compared to NAC. Furthermore, the WA value of treated RAC reduced 9 % when compared to RAC without treatment. Munir et al. (Munir et al., 2021) presented RAC with treated CRA by CH_3COOH immersion and mechanically rubbed show higher compressive strength, higher modulus of elasticity, and lower peak strain compared to unconfined RAC samples.

4.2. Enhancing the quality of adhered mortar of CRA

The primary quality enhancement procedures include filling and condensing the weak areas of adhering mortar and generating stronger ITZs. Table 7 depicts techniques to improve the quality of AM of CRA. It can be observed that various methods can be separated into physical and chemical treatments.

Soluble in-water polymers like polyvinyl alcohol (PVA) have been employed to improve the characteristics of CRA. CRA was soaked in PVA with 6 %, 8 %, 10 %, and 12 % solutions by Kou *et al.* (Kou and Poon, 2010). The density of CRA rose, and WA reduced as PVA solution increased. Tsujino *et al.* (Tsujino et al., 2007) improved the surface of CRA using an oil-type and a silane-type product. The results showed that WA for the oil-type was reduced by 3.5 % and 1 % for the silane-type, resulting in the oil-type significantly decreased WA more than the silane-type product. The oil-type agent can interact with portlandite in the AM to form alkali metal salts, which create an aqueous membrane on the CRA surface and help improve hardening properties.

Calcium carbonate deposition is a new technology utilised to increase CRA quality by minimising WA in the AM. This technique is the capacity of bacteria to expedite the synthesis of $CaCO_3$ on the surface of

Table 6
Summary of methods to eliminate the adhered mortar of CRA.

Treatments to eliminate adhered mortar	Processes	Results	Ref.
Thermal	Crushed RAC was heated around 300 °C	Decrease pores diameter of 0.05 μm or less.	(Choi et al., 2014)
Mechanical	Mechanical milling: use ball-crushing to minimise old mortar	Reduce the quantity of adhered mortar by 62 % and slightly rounder aggregate. WA can be reduced by 50 % compared to the initial WA.	(Dimitriou et al., 2018)
Thermal-mechanical	Use the microwave to warm it up and diminish the initial ITZs between the new and old mortar.	Reduce 32 % old mortar content, 19 % WA, and increase 2.5 % particle density.	(Akbarnezhad et al., 2011)
		Liberation degree of CRA increased by 65.1 %	(Bru et al., 2014)
Chemical	Use HCl, H_2SO_4, H_3PO_4 to remove adhered mortar	WA rates reduce from 7.27 % to 12.17 %.	(Tam et al., 2007)
	Use HCl or Na_2SO_4	Old mortar content was reduced by 6.21 % and 12.59 %, respectively.	(Kim et al., 2018)
Chemical-mechanical	Use ultrasonic water to eliminate old mortar.	Compressive strength increase was about 7 % at 28 days.	(Katz, 2004)
	Heating and scrubbing treatment combined HCl and H_2SO_4	H_2SO_4 removes the adhering mortar of CRA more effectively than HCl. This method improves the quality of the CRA	(Purushothaman et al., 2015)
	CH_3COOH treatment and ball-crushing	Split tensile strengths of 93 %, flexural strength of 94 % compared to NAC Reduced by 7 % of WA compared to RAC without treatment.	(Kazmi et al., 2019; Kazmi et al., 2020)
	CH_3COOH treatment and mechanically rubbed	RAC with treated CRA have higher compressive strength, higher modulus of elasticity, and lower peak strain	(Munir et al., 2021)

the aggregate (Tam et al., 2021). Grabiec *et al.* (Grabiec et al., 2012) proposed biological deposition using Sporosarcina pasteurii (Bacillus pasteurii) bacteria for surface treatment of CRA, claiming that the biological deposition can minimise WA by 21 %. The lowest WA of CRA before and after deposition are 3.6 and 3.1, respectively, with W/C = 0.45. For $CaCO_3$ precipitation, Wang *et al.* (Wang et al., 2017) applied the Bacillus sphaericus LMG 22257 bacterium. The WA of CRA did not demonstrate a significant reduction, resulting in a weight gain of 0.1–0.5 % for CRA.

Incorporating pozzolanic ingredients, carbonation, and Na_2SiO_3 solution are among the chemical treatments used to improve the properties of CRA. Using FA, SF, slag, and metakaolin to enhance the characteristics of adhering mortar is considered a more efficient method. Katz *et al.* (Katz, 2004) advocated treating the CRA with a silica fume liquid impregnation. The surface of the CRA was treated with 10 liters of water and 1 kg raw SF, which improved the surface between the CRA and cement and strengthened the structure of the old paste that was still adhering to the CRA but had broken during the grinding process. Furthermore, Kong *et al.* (Kong et al., 2010) evaluated a triple mixing method (TM) based on surface-coating aggregates with SCMs to a double-mixing method (DM) on the Cl^- penetration resistance of RAC. After 28 days, the charge passed over 9 hours made with TM may be turned down to be approximately identical to that of NAC made with the standard mixing method (NM) due to the SCM reaction with portlandite generated C-S-H gel, which improves the ITZs and their microstructure (Zhang et al., 2016). Zhang *et al.* (Zhang et al., 2018) suggested that CRA's surface was treated with two sulphoaluminate cement (SAC) −based strengthening slurries, with or without basalt powder (BP) resulting in WA was reduced by 9.77 % and 18.83 %, respectively. At 7 and 28 days, the charge passed of samples was decreased by 10.7 % and 9.9 %, respectively. Furthermore, because nano MK consumed portlandite generated and developed C-S-H gel, reducing cracking and failure of ITZs, the microstructure became dense, and the decrease of internal pores and cracks (Xie et al., 2020). Liang et al. (Liang et al., 2022) applied SF added in conjunction with compression cast technique to enhance RAC performance. The results showed that when compared to RAC with normal casting without SF, with the same W/C, the compressive strength improved by 143 %; this technique reduced slightly the elastic modulus, and water porosity dropped to 10.76 % when SF and compression casting were coupled.

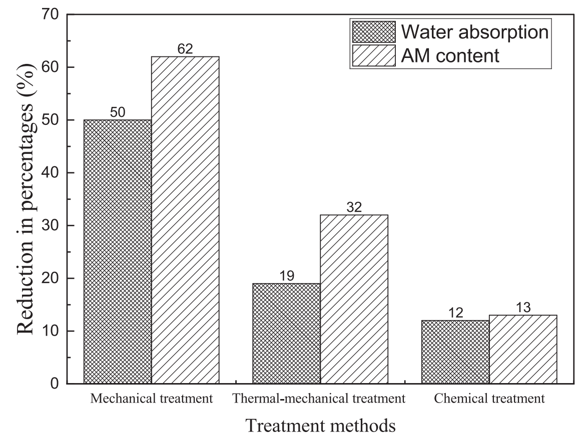

Fig. 7. Effect of treatment methods on properties of CRA (Dimitriou et al., 2018; Akbarnezhad et al., 2011; Tam et al., 2007).

The major hydration products of AM on CRA are portlandite and C-S-H. CO_2 can penetrate the pores of AM to produce $CaCO_3$ (Tam et al., 2016). According to Sereng *et al.* (Sereng et al., 2021), accelerated carbonation enhanced the CRA qualities and extended their use by CO_2 storage in the cement matrix, reducing their environmental effects. The results showed that the porosity dropped by 30 %, and the WA fell by 15 % because CO_2 reacted with portlandite and C-S-H to create calcite and silica gel, which closed the pores of AM (Zhang et al., 2015). According to Xuan et al. (Xuan et al., 2017), the insertion of carbonated CRA in RAC concluded that it not only helped reduce the WA but also decreased its electrical conductivity, chloride diffusion coefficient, and air permeability by 15.1 %, 36.4 %, and 42.4 %, respectively when 100 % carbonated CRA was used. Kazmi et al. (Kazmi et al., 2019; Kazmi et al., 2020) applied lime immersion combined with carbonation to enhance the performance of RAC. The treated RAC exhibits splitting tensile strengths of 90 % and flexural strengths of 75 % compared to NAC. Furthermore, the WA value of treated RAC was reduced by 10 % when compared to RAC without treatment.

Yang *et al.* (Yang *et al.,* 2016) demonstrated that when CRA was treated with Na_2SiO_3 with a modulus of 3.2 and a concentration of 5 %,

Table 7
Summary of methods to enhance the quality of AM of CRA.

Methods to enhance quality adhered mortar	Processes	Results	Ref.
Polymer treatment	Use soluble in-water polymers	WA of CRA with 6, 8, 10, and 12 % PVA concentration are 6.12, 4.63, 4.32, and 4.12 %, respectively, in oven-dried conditions.	(Kou and Poon, 2010)
		WA of CRA with 6, 8, 10, and 12 % PVA concentration are 5.84, 3.17, 2.38, and 2.27 % air-dried.	(Kou and Poon, 2010)
	Oil-type and silane-type agent	WA values are 3.5 % and 1 % for oil-type and silane-type, respectively.	(Tsujino et al., 2007)
Calcium carbonate biodeposition	Using Sporosarcina pasteurii (Bacillus pasteurii) bacteria	Biological deposition can minimise water absorption by up to 21 %.	(Grabiec et al., 2012)
	Applied the Bacillus sphaericus LMG 22257 bacterium	The WA of CRA reduces by 0.1–0.5 %.	(Wang et al., 2017)
Incorporating pozzolanic materials	Treat CRA by SF liquid impregnation.	The compressive strength of RAC after using treated CRA has dramatically increased between 23 and 33 % at age 7 days and between 13 and 16 % at age 28 days.	(Katz, 2004)
	Treated with sulphoaluminate cement combines toxic waste or basalt powder (BP)	After surface treatment, WAs were reduced by 9.77 % and 18.83 %.	(Zhang et al., 2018)
	Apply nano MK consumed $Ca(OH)_2$	The cracking of AM and the failure of the ITZs were reduced, and the microstructure became denser.	(Xie et al., 2020)
	Combining SF and compression casting	The compressive strength rose 143 %, elastic modulus slightly reduced, water porosity dropped by 10.76 % compared to RAC with normal casting and without SF	(Liang et al., 2022)
Carbonation	Accelerated carbonation was used to enhance the CRA qualities	Porosity dropped by 30 %, and the WA coefficient fell by 15 %.	(Sereng et al., 2021)
		Bulk electrical conductivity, chloride, and gas permeability were reduced by 15.1 %, 36.4 %, and 42.4 % when 100 % carbonated CRA was employed.	(Xuan et al., 2017)
	Lime immersion combined with carbonation	Split tensile strengths of 90 %, flexural strength of 75 % compared to NAC Reduced 10 % of WA compared to RAC without treatment.	(Kazmi et al., 2019; Kazmi et al., 2020)
Sodium silicate solution	Treated with Na_2SiO_3 solution	Compressive strength rises by 29 % with treated CRA.	(Yang et al., 2016)

the compressive strength rose by 29 %, and the RAC had outstanding durability. The sodium silicate considerably reduced WA, according to the findings. The Na_2SiO_3 reacted $Ca(OH)_2$ to form C-S-H, which enhanced link between AM and CRA (Song et al., 2016).

5. Discussion and recommendations

There have been substantial studies on the durability of RAC. Most studies focus on examining the factors affecting the durability and treatment methods applied to CRA to improve the quality of concrete. With abundant data, simulation or prediction using machine learning models is a trend in future research. Due to the possibility of non-linear and linked relationships between the deciding parameters, predictions made using artificial intelligence methods correlate with experimental data better than predictions made using regression-based approaches. Fig. 8 shows the models to study RAC's durability properties. It is noted that the percentage of AI models (ANNs, The) is 22 %. Further use of AI models is expected in the upcoming years because of the advantages identified when predicting RAC's mechanical properties (Nguyen et al., 2023; Nunez et al., 2021).

Table 8 summarises the relationships and effect intensities between the parameters concerning RAC discussed in this paper and the RAC durability properties studied in the literature. Incorporating untreated recycled aggregates into concrete increases the D_{eff} of RAC because of the high porosity of CRA. Researchers have highlighted chloride ingress in RAC affected by several parameters such as the constituents of CRA, curing methods, the use of superplasticisers and additives, in addition to a low W/C ratio, which delays chloride ingress because of chloride isotherms (low W/C increases chloride ingress and carbonation of RAC). In addition, the carbonation depth generally grew up with the CRA content. The use of superplasticisers and additives could improve the carbonation resistance. However, the impact of the W/C on carbonation remains unclear in the literature, as shown in Section 3.2. It should be noticed that carbonation of RAC (from concrete waste) before their incorporation into concrete seals their porosity through the formation of $CaCO_3$ in the pores, in addition to the benefit of CO_2 uptake. This improves the transfer properties of RAC. Finally, more data on the water and air permeability of RACs is needed in the literature.

There are several significant conflicts with the durability criteria of RAC, especially with regard to resistance to carbonation and chloride. There is a notable conflict in the W/C ratio because while raising it makes the concrete more workable, it also increases its permeability and D_{eff}, making it more susceptible to carbonation and chloride penetration. In a similar vein, increasing CRA replacement ratio reduces resistance to both deterioration mechanisms by increasing permeability, even though it is good for the environment. This makes striking a compromise between durability requirements and sustainability goals difficult. By lowering permeability and D_{eff}, the addition of SCMs provides some mitigation; however, these positive effects are only moderately strong and might not completely offset the adverse effects of high CRA content. Because increased relative humidity somewhat lowers the carbonation rate and longer curing ages significantly reduce permeability, the curing process introduces yet another level of complication. However, because of the increased moisture content, the humid conditions that aid in preventing carbonation may hasten the entry of chloride. Furthermore, higher D_{eff} results from increased CRA water absorption, making the organism more susceptible to chloride intrusion.

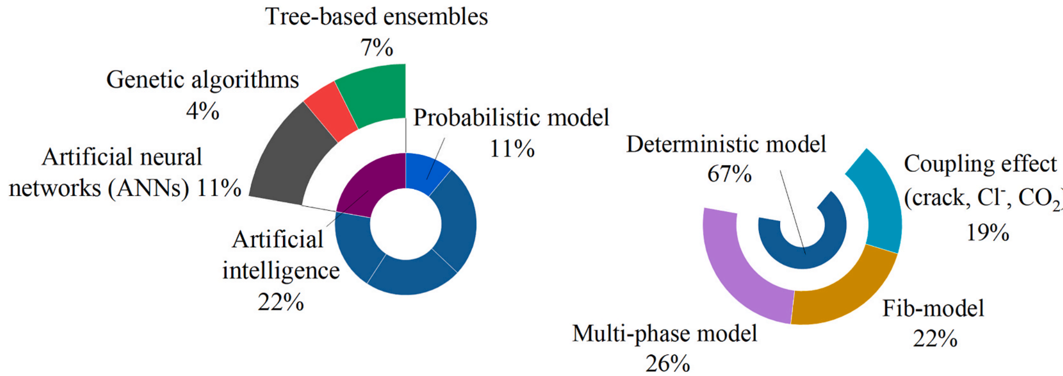

Fig. 8. Models to study durability properties of RAC.

Table 8
Relationship between different parameters of RAC and its durability.

Parameter	Durability properties	Effect intensity
↑ CRA replacement	↑ Permeability	Strong
	↑ D_{eff}	Strong
	↑ Carbonation depth	Strong
↑ W/C ratio	↑ Permeability	Strong
	↑ D_{eff}	Strong
	↑ Carbonation depth	Strong
Source	Permeability	Medium
↑ Curing age	↓ Permeability	Strong
↑ SCMs content: FA, Slag, SF, MK	↓ Permeability	Medium
	↓ D_{eff}	Medium
	↓ Carbonation rate	Medium
↑ Water absorption of CRA	↑ D_{eff}	Mild
↑ Curing condition (Relative humidity)	↓ Carbonation rate	Mild

Table 9
Strengths and weaknesses of different methods to enhance the quality of CRA.

Methods	Strengths	Weaknesses
Mechanical milling	– Easy operation – Effective in reducing adhered mortar	– Create low-quality fine aggregate – Appear micro-cracks inside CRA
Selective thermal grinding, Heat grinding	– Reduce pore size of AM – Improve the ITZs	– Consume high-energy – Create micro-cracks – Create low-quality fine aggregate
Pre-soaking cleaning in acid	– Reduce pore size of adhered mortar – Increase the density of CRA	– Reduce chloride and sulfate resistance of RAC – Environmental problem with a waste solution – Easy corrosion because of low pH
Pre-soaking in water	– Reduce pore size of adhered mortar – Increase the density of CRA	– Low-effective method
Polymer treatment	– Reduce porosity and increase density of ITZs – Decrease WA of RA	– Create the waste solution – High cost
Calcium carbonate deposition Carbonation	– Increase mechanical and durability of RAC – Low cost – Reduce CO_2 emission	– Decrease pH of CRA, resulting in corrosion.
Incorporating pozzolanic ingredients	– Utilise waste industry – Improve the quality of CRA	– High cost – Time-consuming
Na_2SiO_3 solution	– Improve WA of CRA – Improve new ITZs	– Time-consuming – Expensive – Increase alkali-silica reaction

This effect is minor, but it may become important in hostile circumstances.

These opposing features draw attention to how complicated RAC durability is and how enhancing one component frequently means sacrificing another. This calls for careful mix design and application-specific optimization, especially in settings where resistance to carbonation and chloride are essential performance criteria. The difficulty is in striking the best possible balance between these conflicting elements while preserving the concrete's intended workability and mechanical qualities.

Fiber addition and advanced compression casting methods are important developments in improving the performance properties of RAC (Kazmi et al., 2021; Wang et al., 2024). By applying regulated pressure during the casting process, compression casting significantly enhances the microstructure of the concrete, leading to improved particle packing and less void volume. This immediately addresses the permeability problems commonly associated with RAC. Fiber addition, especially from waste materials like tire rubber, gives concrete additional advantages by creating a three-dimensional reinforcement network that improves the bond between recycled aggregates and cement paste, increases tensile strength, and inhibits the spread of microcracks. These two methods work in concert to produce a concrete structure that is stronger and has better durability and mechanical qualities. The basic drawbacks of RAC, such as its propensity for increased permeability and shrinkage, are successfully addressed by this dual enhancement approach, which may also enable larger CRA replacement rates without sacrificing performance.

Almost all studies show that durability of RAC is affected by the AM. This leads to lower durability properties of RAC. Therefore, to improve durability performance, enhancing old mortar quality or reducing adhered mortar content using techniques presented in Section 4 is essential. Table 9 shows the strengths and weaknesses of various methods for improving the quality of CRA. It can be observed that many approaches are utilised in the laboratory to enhance CRA quality. However, applying multiple methods at an industrial scale is still an open question, requiring more research and developments in the future. To get the best results for treating the CRA, it is crucial to consider various economic and environmental factors while applying these treatments, including costs, operation time, and absorbed energy or CO_2 emissions. In terms of treatment approaches for removing AM, in comparison to conventional heating methods, the microwave approach has the benefits of rapid heating and ease of control. Therefore, microwave heating can improve the effectiveness of removing the weakly adhering mortar from the CRA surface. Moreover, by producing differential expansion, fast, selective heating with a microwave can remove the adhering mortar from the CRA. Although mechanical crushing uses more energy than microwave heating does, it is not seen to be advantageous when used on a big scale. Regarding methods for quality enhancement of the AM, polymer treatment and SCMs are promising techniques to enhance the durability properties of RAC because these methods have already been employed for NAC and could easily be deployed for RAC. However, these are still not practical and economical treatment techniques. Using CO_2 for treatment is also sustainable since the carbonation process enhances the CRA's mechanical characteristics and durability performance. It is considered an efficient and sustainable procedure, but it's time-consuming.

Furthermore, a thorough and impartial assessment of techniques for modifying the characteristics of recycled aggregate is required (Wu et al., 2024). To encourage their use in construction, evaluation techniques for RA and RAC thoroughly consider the cost of using RA, environmental impact and the performance of the RAC. While RA uses fewer resources, it necessitates additional steps like crushing, sorting, and pre-treatment, which raises costs. When transportation distances for NA are much greater than those for RA, blended mixes offer the greatest economic advantages. According to Lau Hiu Hoong *et al.* (Lau Hiu Hoong et al., 2021), RA can result in significant cost reductions when used in non-structural applications like walls or paving. According to environmental impact assessments (Kurda et al., 2018), which are frequently carried out with Life Cycle Assessment (LCA), RA conserves natural resources and lowers CDW. However, the environmental benefits may be partially reduced by the increased cement use those results from its higher porosity. Modified RA frequently enhances these qualities, bringing RAC closer to conventional concrete. Roads and non-structural elements are examples of field applications that offer performance data from the actual environment. Compressive strength, affordability, and environmental benefits are all balanced in multi-objective optimization to determine the ideal RA replacement levels; 50 % RA frequently results in a workable and long-lasting compromise. Evaluation techniques guarantee that RA and RAC can satisfy the technical, financial, and environmental requirements for widespread adoption by taking a comprehensive approach to these variables.

Based on the above discussions, the following directions for future research are identified for each of the topics covered in this paper:

- *Prediction of RAC durability performance*: future research should concentrate on the development of AI applications given the proven ability of these models to predict RAC features. These models perform better than conventional regression techniques, especially when it is required to represent interconnected and non-linear interactions between parameters. The main challenge is to obtain enough data to develop comprehensive models. Alternative solutions based on Bayesian Networks (Yu et al., 2024; Nguyen et al., 2025) could be also explored when less data is available.
- *Experimental studies on RAC durability*: Future experimental works should focus on understanding the durability performance of RAC by studying its water and air permeability as well as its resistance to chloride ingress and carbonation under various environmental conditions. Furthermore, the long-term effects of carbonation on RAC, particularly under different curing conditions and CRA replacement levels should be further studied. While carbonation enhances CO_2 uptake, its impact on overall durability it is not fully understood. Since CRA carbonation treatment captures CO_2 in the atmosphere, future research should better assess how this capture influences the construction industry.
- *Improvement of CRA properties*: The creation of effective, scalable, and ecologically friendly techniques for improving CRA properties should be the top priority of future research. Although methods like carbonation and microwave heating provide good results, they must be optimized for widespread use. Treatment strategies need to strike a balance between energy use, cost-effectiveness, and environmental effects such waste production and CO_2 emissions. When evaluating these methods, a thorough LCA should be included. Studies examining the combination of several CRA treatment techniques, such as mechanical crushing combined with carbonation or polymer treatment, may also improve ITZs and reduce porosity.

6. Conclusions

The first part of the paper presented a comprehensive review of modelling approaches (deterministic, probabilistic, and artificial intelligence) used to predict the chloride penetration, carbonation, and permeability of RAC. The impact of CRA's properties, RAC composition, and curing, which were experimentally measured, was discussed in the second part. The third part focused on treatment methods for improving CRA characteristics. Drawings from this review include the following conclusions:

- Chloride ingress, carbonation, and water and air permeability are related to non-linear and multivariable processes. The components that influence RAC durability are interconnected, and modelling the entire process is challenging. As a result, non-linear approaches should be used for durability prediction. Several neural network-based theories have been applied in addition to existing models, such as the Fib or Xiao and Lei's model for carbonation, Fick's law, or the Poisson-Nernst-Planck equation for chloride transport. Based on the complexity of the problem, multi-phase geometrical approaches for modelling chloride or CO_2 reactive transport in RCA are recommended.
- The AM in CRA determines and influences the durability of RAC. The higher porosity and WA of AM resulted in poorer durability. RAC possesses two ITZs, RA – new ITZs and RA – old ITZs. The ITZs create a weak link in the RAC, which comprises many micropores and microcracks and significantly impacts durability. Increased CRA content decreases RAC's impermeability, chloride, and carbonation resistance.
- The durability of RAC is improved by strengthening the microstructure, eliminating or enhancing the performance of AM. Both are efficient ways of enhancing the pore structure and strengthening the ITZs layer, leading to enhanced durability properties of RAC. Of the above methods, CRA carbonation is a promising method that is an environmentally friendly treatment and decreases the influence of RAC on the environment regarding technical, economic, and social aspects of CDW application.

CRediT authorship contribution statement

Tien-Dung Nguyen: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Rachid Cherif:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Pierre-Yves Mahieux:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Philippe Turcry:** Writing – review & editing, Investigation, Conceptualization. **Emilio Bastidas-Arteaga:** Writing – review & editing, Supervision, Project administration, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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