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Effect of enhancement treatments applied to recycled concrete aggregates on concrete durability: A review

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ABSTRACT: Recycled concrete aggregates (RCAs) have been demonstrated as an alternative source to exhaustible natural aggregates. In this paper, we focus on the enhancement treatments for coarse and fine RCAs and the effect of these treatments on the durability of recycled concrete (RC) made from treated RCAs by the weakening and strengthening of the cement paste adhered to their surface. We conducted comparative analyses on the improvement of durability and mechanical properties. The results showed that the reduction of water absorption in RCAs increases the compressive strength of RC and that there is a strong linear trend of improvement in the carbonation depth, chloride ion penetration, and compressive strength of RC. For fine and coarse RCAs, the treatment mechanism and particle size are determinants in efficiently improving RC durability.

KEY WORDS: Recycled concrete aggregates; RCA enhancement treatments; Concrete carbonation depth; Concrete chloride ion penetration; RC compressive strength.

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RESUMEN: *Efecto sobre la durabilidad del hormigón de los tratamientos de mejora aplicados a los áridos del hormigón reciclado: una revisión.* El uso de áridos de hormigón reciclado (RCA) ha demostrado ser una fuente alternativa a los áridos naturales agotables. Este trabajo se centra en los tratamientos de mejora de los RCA, tanto gruesos como finos, y su efecto en la durabilidad del hormigón reciclado (RC) a partir de tratamientos por debilitamiento y fortalecimiento de la pasta de cemento adherida a su superficie de los RCA. Se llevaron a cabo análisis comparativos sobre la mejora de la durabilidad y las propiedades mecánicas, permitiendo identificar que la reducción de la absorción de agua de los RCA conduce a un aumento en la resistencia a la compresión del RC, y que existe una fuerte tendencia lineal de mejora de la profundidad de carbonatación, la penetración de iones cloruro y la resistencia a la compresión, donde el mecanismo de tratamiento y el tamaño de partícula son determinantes para lograr una mejora eficiente de la durabilidad del RC.

PALABRAS CLAVE: Áridos de hormigón reciclado (RCA); Tratamientos de mejora de RCA; Profundidad de carbonatación; Penetración de iones cloruro; Resistencia a la compresión de RC.

1. INTRODUCTION

The demand of the construction industry regarding urban development is associated with the increasing use of building materials. Concrete is the most widely used artificial material in the world; thus, abundant construction and demolition concrete waste is produced (1, 2). The concrete industry produces approximately 25000 metric tons of waste annually (3). Additionally, aggregates, which account for up to 70% of a concrete mix, are globally consumed in construction at approximately 26000 metric tons annually (4). As consumption rates continuously increase, the demand for aggregates is expected to double in the next two to three decades. This condition presents a challenge to sustainability during the life cycle of concrete, from its production to its use and final disposal or reuse.

Several studies (5-8) have identified that at the end of its useful life, concrete can be crushed into adequately sized particles to be used as aggregates (coarse or fine) in new mixtures of recycled concrete (RC) or recycled mortar (RM). Crushed particles are usually classified as coarse aggregates if they are larger than 4.75 mm and fine if smaller. However, a reduction in RC performance has been reported as a function of the increased percentage of replacement by recycled concrete aggregates (RCAs), a condition directly associated with their highly porous nature (9-15). Thus, RCAs have inferior properties compared to natural aggregates (NAs), which include increased water absorption and reduced density (16-19). Consequently, the mechanical behavior and durability of RC and RM made using RCA are lower than those made using NAs (20-23). Therefore, consistent with Sereng et al. (2021) and Li et al. (2022) through an improvement treatment of RCAs, their high water absorption can be decreased and, subsequently, the optimum water content in the RC mixture can be found by correcting the moisture content (24, 25). Thus, a transient decrease in RC porosity and an increase in the resistance of aggressive agents are expected.

Previous studies have mainly focused on the mechanical and microstructural behavior of RC made with treated RCAs. Studies have investigated the effect of each treatment on the durability of RC. Therefore, there is still a long road ahead in terms of the relationship between the mechanical properties and the durability performance of concretes made with treated RCA. In this paper, we review the previous results of the existing improvement treatments (weakening or strengthening of the residual bonded cement layer to the coarse and fine RCAs) and their effect on the durability of RC made with treated RCA. We construct graphs that provide a comparative analysis to illustrate the effect of each treatment.

This study is expected to contribute to the selection of improvement treatments effective enough to achieve enhanced replacement of NA in concrete and mortar mixes. The work was conducted following a systematic literature review, where 117 research articles from 2003 to 2022 were reviewed, using Scopus, ScienceDirect, and SpringerLink as sources.

2. METHODS OF IMPROVING RC AGGREGATE QUALITY

The use of RCA in concrete has been limited due to its high water absorption, elevated porosity, and poor microstructure properties, especially at the interface transition zone (ITZ) between a new cement matrix and RCAs (ITZ_1) and a new cement matrix and the old cement paste surrounding natural RCAs (ITZ_2) (26). Most of these zones are weak due to continuous cracks and fissures resulting from the crushing process (27-29). Figure 1 shows the RCA transformation process, their physical characteristics, and their interaction within a concrete matrix, compared to a NA.

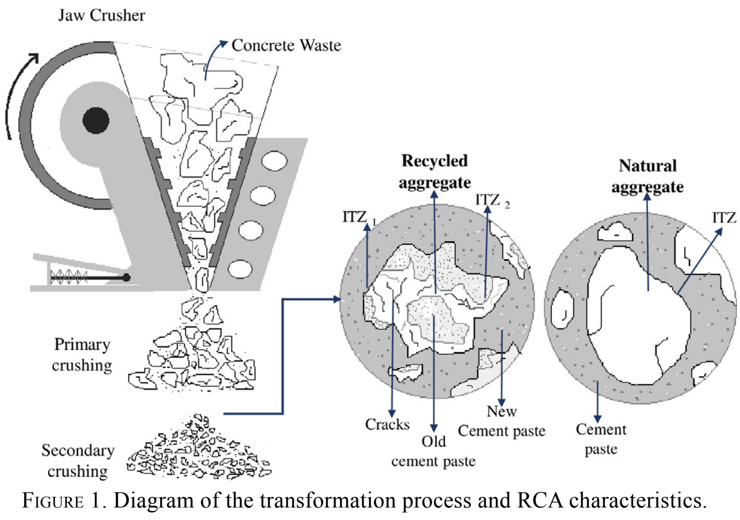

Figure 1. Diagram of the transformation process and RCA characteristics.

Cement paste bonded to the surface of RCAs has been reported to be extremely porous (up to 20 times higher than that of NA), which depends on the volume of cement paste bonded to the RCA (30). Thus, the RCA exposed to moisture can absorb more water than NA. Therefore, water absorption and the degree of porosity have been indicated as key parameters in determining the mixing performance, mechanical performance, and durability of RC made from RCA (31, 32).

In this context, several methods have been proposed to treat the cracks resulting from the transformation processes, and the cement paste adhered to the surface of RCAs. Treatments have been reported from chemical, thermal, and mechanical processes (Table 1).

Table 1. Depth of treatment investigation.

Treatment[1]	In-depth studied[2]	
	Fine RCA	Coarse RCA
Soaking	+++	+++
CO_2 curing	++	+++
Coating	++	+++
Biodeposition	+	+++
Mixing/Rehydrating	+	++
Heating	+	++
Rehydrating	−	+++
Coating/Heating	−	++
Mixing/Coating	−	++
Heating	−	++
Crushing	−	+
Cleaning/Heating	−	+
Soaking/ Impregnating	−	+
Grinding	+	−
Heating/Grinding	+	−
Heating/Rehydrating	+	−

[1] All treatments are referenced by groups in Table 2.
[2] (+++): highly studied; (++): moderately studied; (+): lowly studied; (−): not studied.

The treatments can be classified into two groups. The first group focuses on weakening the residual bonded cement layer in the RCAs, and the second group focuses on strengthening the bonded cement layer and cracked surface of the RCAs, which has demonstrated a densification of the structure and an increase in their physical and mechanical performances. Table 2 lists a summary of the different treatments, which have been investigated by different authors individually and jointly to improve RCA quality.

Considering that the improvement of the RCAs is mainly evidenced by the decrease in porosity, the results in Table 2 show that regardless of the treatment applied, a decrease in water absorption is related to an increase in compressive strength. However, although a potential improvement is identified when applying the treatments, significant differences are found between them. Some treatment methods focus on improving the aggregate density of RCAs by removing the bonded cement paste, while others focus on improving the concrete quality by providing additional density (41, 93). In addition, the mechanical performance and durability of fine and coarse RCAs depend on the source characteristics and age of the original concrete (4, 14).

2.1. Relationship between the water absorption of treated RC aggregrates and the compressive strength of RC

In this study, the results of reported treatments are obtained, specifically the percentage decrease in the water absorption of RCAs and the increase in the compressive strength of RC at 28 days, substituting 100% treated and untreated RCAs. The relationship between the water absorption of RCAs and the compressive strength of RC is shown in Figure 2, where coarse RCA particles are between 4.75 and 20 mm, as well as in Figure 3, where fine RCA particles are less than 4.75 mm. All treatments that show a standard deviation have been extensively studied.

Compared to fine RCAs, the improvement in coarse RCAs quality has been more relevant in terms of number of proposed treatments, especially treatments that weaken the cement paste that adheres to the RCA surface (see Table 1). This result is explained by the fact that an increase in the particle size eases cement paste removal. In contrast, the results of the strengthening treatments for coarse and fine RCAs are significant, where an efficiency in compressive strength is approximately two and six times higher for coarse and fine RCAs, respectively, compared to the weakening treatments (see Figures 2 and 3).

For coarse RCAs treated with weakening methods (Figure 2), acetic acid soaking is preferred to improve absorption by only 20%, which also increases compressive strength by approximately 20%. This result is mostly caused by the reaction of acetic acid with the hydration products of the cement bonded to the RCA surface. This reaction weakens the bonded mortar, allowing it to be removed by subsequent mechanical rubbing (51, 52). However, the degree of adsorption in RCAs reportedly increases with the acetic acid concentration because it dissolves more hydration products; thus, increased porosity may be generated (34, 51). Meanwhile, to decrease absorption by 20% to 40% or more, scrubbing/crouching treatment is employed, which gives the greatest improvement in compressive strength (approximately 30%). According to Pandurangan et al. (35), in this case, the RCAs are treated using a Los Angeles abrasion machine, and the amount of mortar still adhered to the coarse RCAs after treatment is around 5%. The specific gravity is also improved (39).

TABLE 2. Summary of the methods in the literature to improve RCA quality.

Group	Treatment type		Approach/Products	Decreased absorption (%)	Compressive strength improvement of RC (%)	RCA replacement (%)	w/b
Weakening (residual cement paste layer)	*Heating* *Heating/Grinding* *Heating/Rehydrating*	(33-37)	•Dehydration of cement hydration products (endothermic reactions)	[3–60]	[1.9–2.3]	100	[0.34–0.5]
	Crushing Jaw *Crushing-Ball mill* *Scrubbing/Crushing*	(35, 38, 39)	•Mechanical actions, generating thermal and mechanical stress difference	[0.3–32]	[10–17]	100	0.50
	Cleaning *Cleaning/Scrubbing* *Cleaning/Heating*	(40, 41)	•Ultrasonic or water rubbing to remove the attached cement paste	[0–50]	[0–29]	100	0.45
	Soaking (acids)	(17, 34, 39, 42-52)	•Hydrochloric acid (HCl)$CaO + 2HCl \rightarrow CaCl_2{\cdot}H_2O$ $Al_2O_3 + 6HCl \rightarrow 2AlCl_3{\cdot}3H_2O$ $Fe_2O_3 + 6HCl \rightarrow 2FeCl_3{\cdot}3H_2O$ •Sulfuric acid (H_2SO_4) $CaO + H_2SO_4 \rightarrow CaSO_4{\cdot}H_2O$ $Al_2O_3 + 3H_2SO_4 \rightarrow Al_2(SO_4)_3{\cdot}3H_2O$ $Fe_2O_3 + 3H_2SO_4 \rightarrow Fe_2(SO_4)_3{\cdot}3H_2O$ •Phosphoric acid (H_3PO_4) $2CaO + H_3PO_4 \rightarrow 2Ca^{2+} + H^+ + PO_4^{-3} + 2OH^-$ $Al_2O_3 + 2H_3PO_4 \rightarrow 2Al^{3+} + 3H^+ + 2PO_4^{-3} + 3OH^-$ $Fe_2O_3 + 2H_3PO_4 \rightarrow 2Fe^{3+} + 3H^+ + 2PO_4^{-3} + 3OH^-$ •Acetic acid ($C_2H_4O_2$): $CaO + C_2H_4O_2 \rightarrow C_4H_6O_4Ca + H_2O$ $Al_2O_3 + C_2H_4O_2 \rightarrow Al(CH_3COO)_3 + H_2O$	[6–40]	[1.3–25]	[25–100]	[0.38–0.5]
Strengthening (residual cement paste layer)	*CO_2 Curing*	(18, 51, 53-65)	•Carbonation $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$ $C{-}S{-}H + CO_2 \rightarrow CaCO_3.S.iO_2.H_2O$	[6–32]	[6–33]	100	[0.48–0.6]
	Biodeposition	(66-69)	•Sporosarcina pasteurii bacteria *Sp. Cell - $Ca^{2+} + CaO_3^{2-} \rightarrow$ Sp. Cell* - $CaCO_3$	[15–20]	[20–35]	100	[0.4–0.5]
	Coating *Coating/Impregnating* *Coating/Heating*	(18, 43, 62, 70-82)	•Silane emulsion *$Si{-}OC_2H_5 \rightarrow Si{-}OH \rightarrow Si{-}O{-}Si$ bond* •Pozzolans (*Silica fume, Fly ash, bland furnace*) *Convert CH crystals → C–S–H gel* •Nanomaterials *Pozzolanic reaction (early-age) → C–A–S–H gel* $SiO_2 + Ca(OH)_2 + Al_2O_3 \rightarrow CaO.SiO_2.H_2O$	[15–84]	[0–58]	[25–100]	[0.38–0.50]
	Mixing *Mixing/Coating* *Rehydrating/Mixing*	(21, 83-88)	• Mixing in two or three stages, and the addition of pozzolanic materials (silica fume and blast furnace slag). *Reactions with $Ca(OH)_2$ → new hydration products*	[32–8]	[6–45]	[20–100]	[0.4–0.55]
	Soaking (solutions–acids)	(43, 70, 50, 89-92)	•Diammonium hydrogen phosphate -DAP $10CaCO_3 + 6HPO_4^{2-} + 2OH^- \rightarrow Ca_{10}(PO_4)_6(OH)_2(s) + 7CO_3^{2-} + 3CO_2 + 3H_2O$. • Sodium silicate $Na_2SiO_3 + Ca(OH)_2 + H_2O \rightarrow CaO.SiO_2.H_2O + NaOH$. •Tanic acid *React with CH and calcite → nanoparticles*	[4–79]	[1.3–25]	[15–100]	[0.38–0.50]

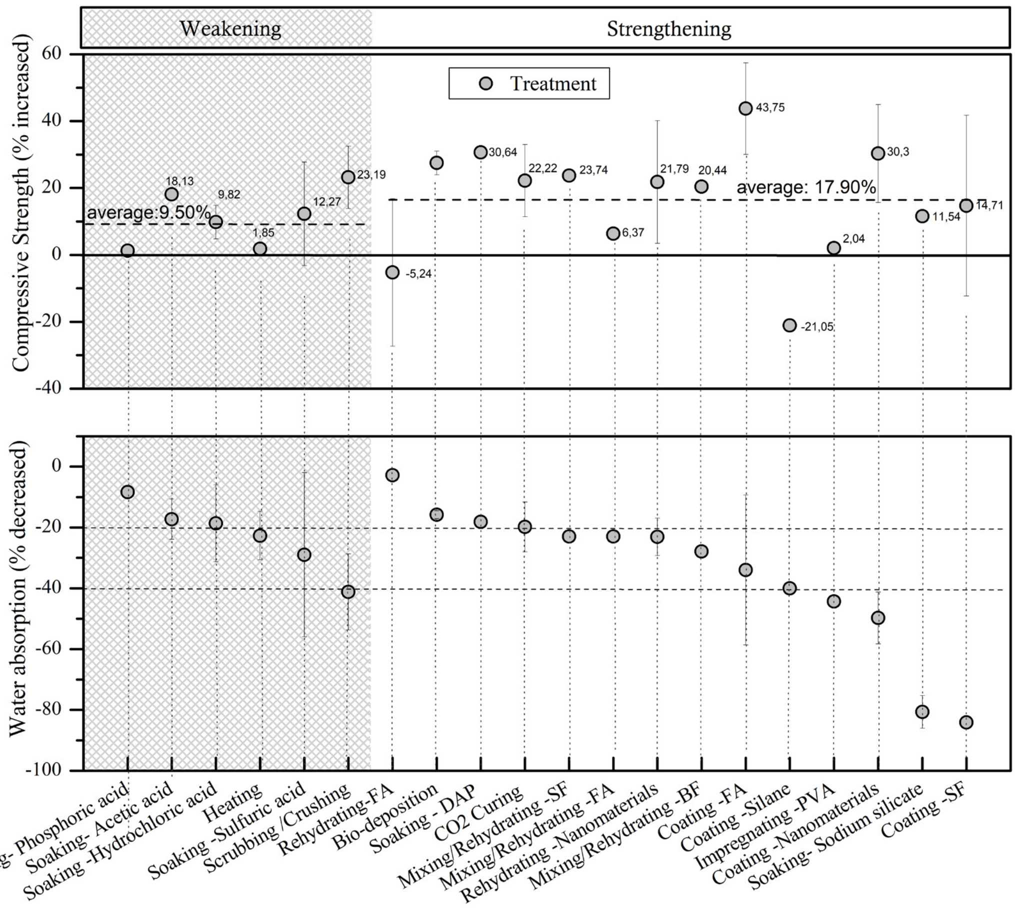

Figure 2. Relationship between the water absorption of coarse RCAs and the compressive strength of RC under different treatments.

For coarse RCAs treated with strengthening methods (Figure 2), although rehydration using fly ash (FA) significantly improves strength, it is not directly attributed to the improvement in the RCA quality but to the effect of adding the concrete mix. Therefore, the absorption value decreases, which is not highly significant. In this sense, soaking in diammonium hydrogen phosphate (DAP) favorably increases the concrete strength of treated RCA (approximately 30%), which results in a decrease in water absorption (approximately 20%). This result is due to the reaction between DAP and hydration products rich in free calcium (portlandite) on the RCA surface, which produces hydroxyapatite complexes responsible for achieving a pore-refining effect (90). Conversely, to improve absorption by 20% to 40% or more, FA or silica fume (SF) coating is the optimal treatment, which can increase compressive strength by over 50%. In this case, coating the RCA surface with a pozzolanic material, which is one of the most common methods, has been shown to improve the bond between RCA and new mortar (79). The process involves creating a pozzolanic powder slurry using FA or SF and subsequently incorporating RCA into the slurry. Its main effect is due to the filler effect of the pores on the RCA surface, which develops a stronger ITZ due to the pozzolanic reaction over time (81).

Finally, some treatments have reportedly shown no significant effect on compressive strength. Other studies with rehydration (FA) and coating (silane) have reported adverse effects in which compressive strength decreases. Thus, the study conditions should be investigated in detail to establish the feasibility of their application.

Figure 3 shows the data for fine RCA treated with weakening methods. Although there is a significant improvement in the percentage water absorption using acetic acid and hydrochloric acid (HCl) soaking, the increase in compressive strength is not more than 10%. These results, reported at a low significance level, verify that particle size influences the treatment effect because fine RCAs have a greater specific surface area than coarse RCAs. This implies an increase in the reaction kinetics, which generates an opposite effect. Furthermore, according to Tam et al. (41), focusing on the concentration level and time of treatments with acids, such as HCl and sulfuric (H_2SO_4) acids, is important due to the possible increase in the chloride and sulfate content, which affects the durability of concrete made from treated RCA and presents a health risk.

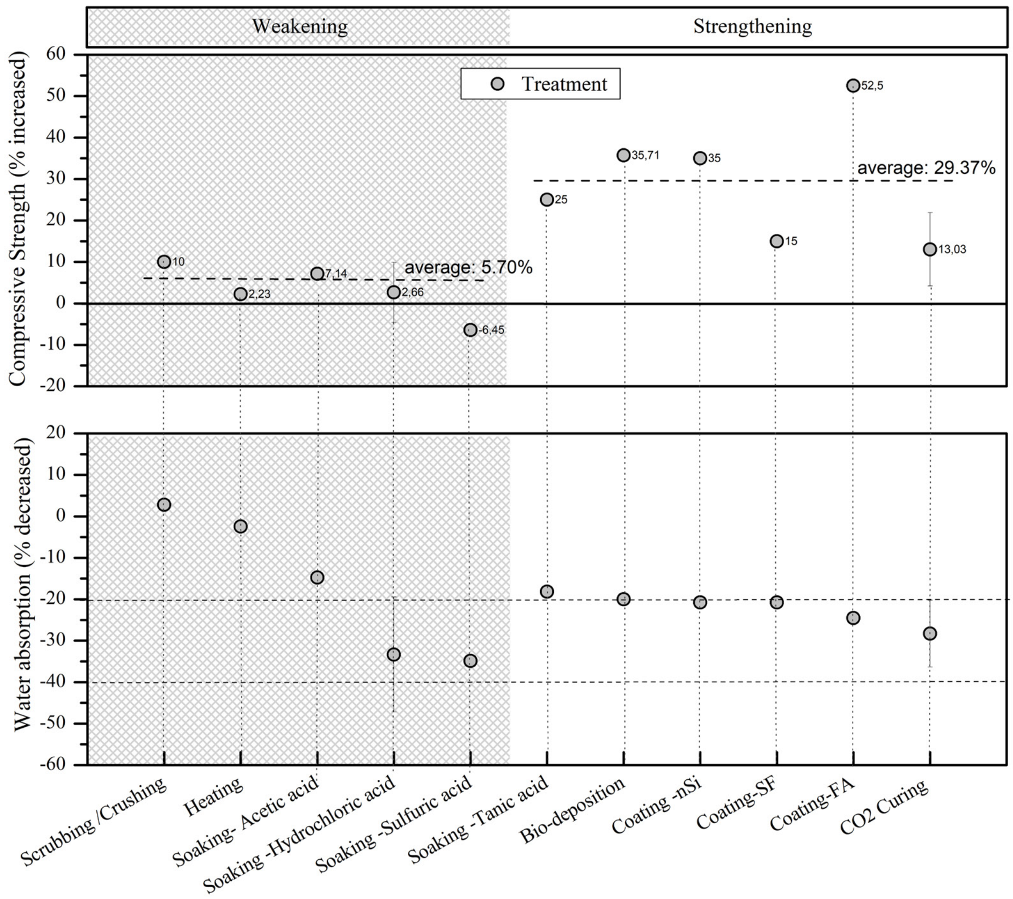

FIGURE 3. Relationship between the water absorption of fine RCAs and the compressive strength of RC under different treatments.

The scenario for fine RCA is promising with treatments that strengthen the cement layer attached to their surface (Figure 3). To improve absorption by approximately 20%, biodeposition- and nanosilica (nSi)-coating treatments are available, which increase the compressive strength by approximately 40%. The biodeposition method is based on the ability of bacteria, specifically *Bacillus pseudofirmus*, to produce calcium carbonate on the cell surface in the presence of suitable calcium sources. Chun-Ran Wu et al. (68) clarified that during biodeposition treatment, calcium carbonate formation was influenced by external factors, such as particle shape, size, and bacteria concentration. Similarly, Singh et al. (94) found that due to its high pozzolanic reactivity, nano-SiO_2 effectively improves RCAs quality. They concluded that the treatment effectiveness depends on the type, particle size, and reactivity of the employed pozzolan, as well as the calcium-hydroxide content that remains in the bonded cement paste for the pozzolanic reaction. In addition, Caijun Shi et al. (18) found that nSi coating treatment was effective in improving the quality of old and new ITZs of RC made with treated RCAs. However, a slight reduction in the mixture fluidity occurs because of the high specific surface area of the nanoparticles.

Figure 3 also shows a couple of treatments that reduce the water absorption by more than 20% (SF coating and CO_2 curing). Although the CO_2 curing of fine RCAs achieves a larger reduction in water absorption than SF coating, the improvement in the concrete strength of RCAs treated with SF coating is higher than that of CO_2 curing. This improvement is mainly attributed to the accelerated carbonation of portlandite (CH), which forms calcium carbonates with a large solid volume that fill the pore spaces and thus densify the microstructure (59). Chinzorigt et al. (95) found that the effect of carbonation on RCAs occurs mainly on the RCA surface and that the strength of the cement paste bonded on the RCA surface does not seem to show significant improvement because no carbonation occurs toward the interior. As demonstrated in several studies, CO_2 curing treatment is seemingly effective in increasing RCA quality and improving the hardening properties of RC, especially its mechanical properties. Conversely, research on the durability properties of concrete obtained with carbonated RCA is still limited and does not adequately optimize the concrete mix design for effective environmental benefits (65).

3. DURABILITY OF RC AND MORTARS MADE WITH RCAs

Concrete durability is related to the serviceability and structural requirements over its expected life (96). It is a measure of the performance characteristics against aggressive environmental agents, such as sulfates, chlorides, and carbon dioxide, which are directly related to permeability. The foreign agents move through concrete by flowing through the porous system and diffusion and sorption, which introduces corrosion hazards to the steel reinforcement. The performance of an RC is mainly linked to the physical characteristics of the RCA. In this sense, the following two factors would have the maximum effect in assessing the long-term performance of RC:

- The effect of high water absorption, which affects the water/cement (w/c) ratio and hydration processes (17, 32).
- The weak microstructure due to all ITZs present in an RC (97).

The properties related to RC durability have been extensively studied (98-100). However, regarding the influence of RCA improvement treatments on the durability properties, carbonation and chloride ion resistance have been studied the most, especially in RC with coarse RCAs (101, 102). As previously mentioned, the focus of the different treatments has been on evaluating the mechanical and microstructural properties of RC and, on a smaller scale, on its durability properties.

3.1. Permeability of RC

In RC, an increase in the volume of cement paste adhered to the RCA surface and the number of cracks or fissures increases the porosity, promoting the transport of external agents and thus reducing mechanical and durability performances (101, 103, 104). A negative effect is more evident for RC with fine RCAs than with coarse RCAs due to the increased specific surface area (105). Thus, the reduction in RC permeability is related to the RCA particle size.

According to the results reported by D. Pedro et al. (2017) and D. Brito (2016), fine RCAs affect RC permeability more than coarse RCAs due to the increased number of capillary channels in the concrete system. Conversely, the superior size of coarse RCAs results in a reduced surface area, thus reducing the amount of water required and increasing RC permeability (88, 106). For example, in Figures 2 and 3, regardless of the enhancement treatment used, coarse RCAs tend to show higher percentages of water absorption reduction (about twice as much) than fine RCAs. This behavior is associated with the fact that thin RCAs have a higher content of cement paste adhered to their surface.

In contrast, related to the effect of fine RCA content on RC permeability, Basheer et al. (107) found that an increase in fine RCA content decreased air permeability, concluding that increased flow path tortuosity contributed to this effect. According to their results, RCAs with an inferior average size and an efficient improvement treatment based on particle size should be used to improve the air permeability of RC.

3.2. Carbonation of concretes with treated RCAs

The resistance of RC to carbonation is observed to be poorer than that of conventional concrete due to its porosity (101). In particular, the carbonation depth of RC can reach five times that of conventional concrete (108, 109), which can increase with an increase in the RCA content (10) and w/c ratio (110, 111). Furthermore, according to the literature, the carbonation thickness ratio varies from 1.0 to 2.5 for coarse RCA substitution and 1.0 to 8.7 for a fine RCA (11).

Figure 4 shows the effect on carbonation depth of some treatments applied to RCAs (treatments presented in Table 2), where a correlation between carbonation depth and compressive strength of RC after 28 days of curing, made from treated fine or coarse RCA, is observed.

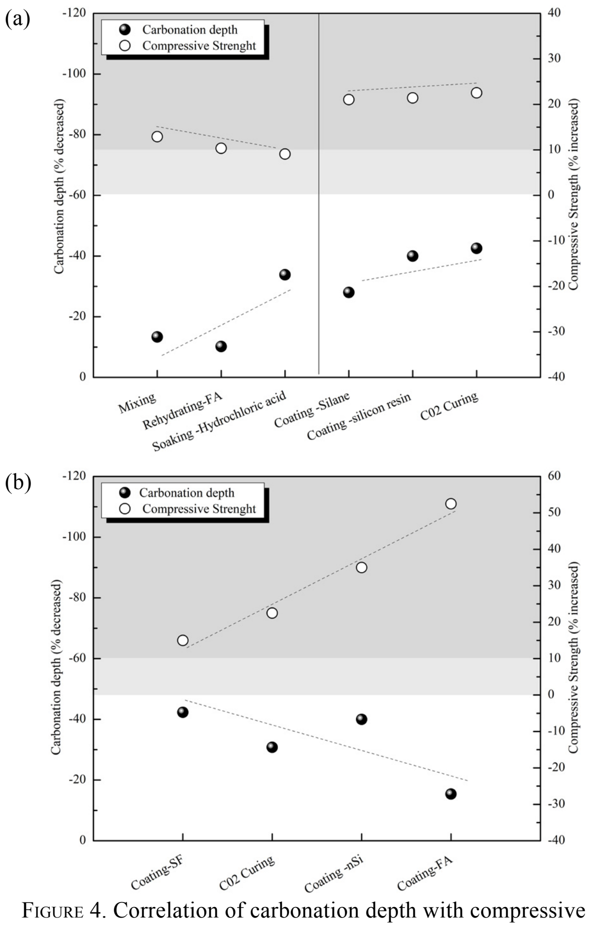

FIGURE 4. Correlation of carbonation depth with compressive strength. (a) RC with coarse RCAs. (b) RC with fine RCAs.

For coarse RCAs, the applied treatments showed two tendencies (Figure 4(a)). The first shows that the treatments reduce the carbonation depth, but the compressive strength tends to decrease, indicating a somewhat insignificant improvement of approximately 10%. The second allows identification of treatments where, in addition to exhibiting a significant reduction in the carbonation depth (between 25% and 40%), a linear trend appears with increasing compressive strength (approximately 25%). In this case, the treatment with maximum improvement is the CO_2 curing treatment. These results are consistent with those of previous research. Levy et al. (112) found that the carbonation depth is lower when recycled aggregates (100% substitution) are used compared to concrete made with NAs. They associated this result with the alkaline reserve of RCAs (which is superior and acts as a protective barrier). Thus, this positive effect of the alkaline reserve on carbonation provides a beneficial relationship with the service life of RC, which can delay the possible corrosion of steel. Further, CO_2 curing treatment reportedly provides a major beneficial effect on the durability properties of RC, showing a strong correlation between water absorption and permeability and suggesting that the water absorption value of RCAs can be used as a criterion for RC durability (57).

Regarding fine RCAs, which are widely used in practice, a reduction in mortar and concrete strength has been reported; therefore, replacing fine RCAs by not more than 30% has been proposed (113, 114). Considering this, treatment of fine RCAs is necessary. Figure 4(b) shows that, according to the reported studies, a trend line can be drawn using four treatments (SF coating, nSi coating, CO_2 curing, and FA coating), which shows that a proportional improvement in carbonation (decrease in carbonation depth) is correlated with compressive strength (largely significant up to 55% for SF coating). In this case, the use of pozzolan is more effective than other treatments due to the pore refining effect on the structure, especially in old and new ITZs. Additionally, a reduction in the flowability of mixtures when SF and nSi are used has been reported, which is due to the large specific surface area of these materials (18, 40). This result suggests combining the carbonation methods with fine RCA and rehydrating the mixtures with pozzolanic materials.

3.3. Chloride ion penetrability of concretes made with treated RCAs

Chloride ion migration has been shown to be a determining factor in concrete durability, especially because it promotes the corrosion of steel in reinforced concrete (48, 81). The penetration of chloride ions into concrete is also related to carbonation: when carbonation (reduction in porosity at the concrete surface) occurs, the free chloride content in the carbonated region decreases (60, 115). Thus, replacing NA with RCA can enhance the formation and propagation of cracks, which increases the risk of corrosion (116, 117). However, studies on this subject to identify the effect of treated RCA on the long-term performance of RC are few.

Figure 5 shows the effect of various treatments on the penetration of chloride ions into the RC with treated coarse RCAs (Figure 5(a)), where four regions of enhancement are defined. In all cases, chloride ion penetration is reduced. When correlated with compressive strength, some regions (Region 1) do not show a significant effect (less than 10% improvement). In improving the compressive strength by approximately 10%, the combined effect of FA mixing/rehydrating reduces the chloride ion penetration due to the filling of pores and cracks in the cement paste bonded to the RCA surface (which decreases the RC porosity) and the high alumina content of FA (which can bind more chloride ions and thus increase the electrical resistivity of concrete) (86).

The last two regions show an improvement in both chloride ion penetrability and compressive strength, where we observe that the SF mixing/rehydrating, SF coating, and nanomaterial coating treatments produce a mostly significant improvement. The improved reduction in chloride permeability for the SF and nanomaterial treatments is mainly due to the pore-filling effect of SF, owing to its small particle size compared with other supplementary materials. Additionally, Faysal et al. (86) found that the effectiveness of supplementary materials against chloride migration depends on their pore-refining effect, which tends to increase the electrical resistivity of concrete. Conversely, the chemical reaction between chloride ions and tricalcium aluminate decreases electrical resistivity due to the decrease in free chloride ions.

For fine RCAs (Figure 5(b)), the results are organized as a linear response that reflects the increase in compressive strength and decrease in chloride ion penetration. These results are consistent with those of Zhang et al. (75), which showed that a nano-SiO_2-treated RCA enhances a new ITZ in RC and contributes to preventing chloride ion migration over time. In summary, it is possible to identify that carbonation treatments are the most reported method to improve the quality of RCAs. As mentioned above, this result is attributed to the formation of calcium carbonate during carbonation, which contributes significantly to the blocking of the pore network, and the transport of external agents (liquids and gases) in RC being majorly controlled by the pore network properties and the degree of water saturation (59).

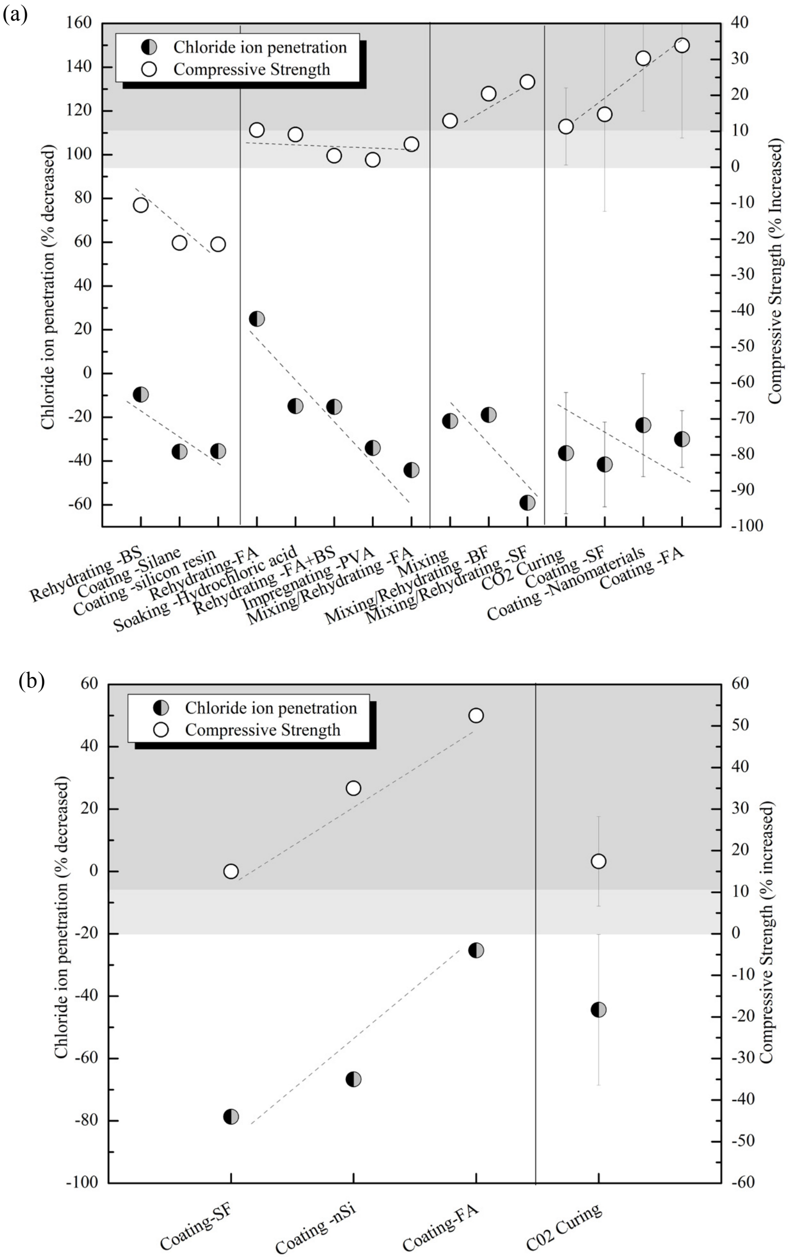

FIGURE 5. Correlation of chloride penetration with compressive strength. (a) RC with coarse RCAs. (b) RM with fine RCAs.

4. CONCLUSIONS

- Regarding the durability of RC from treated fine and coarse RCAs, it is relevant to establish the relationship between chloride penetration coefficient and carbonation depth with the compressive strength (28 days of curing), from which the effect of the treatments on RC permeability (directly related to porosity and weak ITZ) was identified. In both cases, a strong linear trend exists between durability and mechanical strength in most treatments. That is, an increase in compressive strength leads to a decrease in carbonation depth and chloride ion penetration; thus, the absorption results in the treated RCA strongly correlate with the durability results because a considerable improvement in compressive strength is obtained when the degree of absorption in the RCA is reduced. Thus, pozzolan coating and CO_2 curing treatments are the most studied treatments regarding durability, where the former improves the bond between the RCA and the new mortar, achieving a stronger ITZ, and the latter has a pore-filling effect on the RCA surface to prevent the transport of aggressive agents, thus improving the durability of the material.

- When comparing the weakening and strengthening treatments, a continuous improvement in the mechanical strength of RC made with RCAs improved by strengthening treatments was observed. This is consistent with the literature, reporting about six times more effectiveness for fine RCA and about two times more effectiveness for coarse RCA. The significant improvement in the RCA quality is mainly achieved from a balance between the type of treatment and the size of the RCA, as both the pore structure and the RCA surface are modified, which is noted in the strengthening of the hydration product reactions and in the creation of new products that allow the pore structure to be refined. Conversely, compared to fine RCA, the improvement in the quality of coarse RCAs has been more common, especially with the treatments that weaken the cement paste bonded to the surface. This result is explained by the fact that an increase in particle size eases the removal of the cement paste. For fine RCAs, the particle size complicates the weakening action so that strengthening treatments improve the surface and pore structure. In this sense, strengthening treatments are recommended for fine RCAs, and weakening treatments should be complemented with some strengthening treatments for coarse RCAs.
- The study results validate the importance of the water absorption of the RCA in the mixture design of an RC since all mixes need to be corrected for moisture to achieve the design w/c ratio. Therefore, the different treatments in the RCA reduce the water absorption percentage, reducing the error associated with the moisture setting and, in turn, improving mechanical and durability performance. For coarse RCAs, the 30% decrease in water absorption for pozzolan coating is the optimal treatment, increasing compressive strength by over 50%. For fine RCAs, although CO_2 treatment achieves a superior absorption reduction, the improvement in the concrete strength of pozzolan-treated RCAs is superior, suggesting further research on the combination of both treatments.
- This review paper has presented a summary of RCA treatments and their effect on some durability properties of RC. The results will help future research to advance in this field. Although the durability performance of RC has been found to be generally inferior to that of conventional concrete, a possible improvement is identified by applying treatments based on strengthening the cement paste attached to the RCA surface.

5. FUTURE PROSPECTS

- Performance of RC made from RCA improved under hybrid methods.
- Effect of treatments on different particle sizes of RCA and shredding types.
- Environmental and cost assessment of RCA treatments.
- Long-term behavior of steel corrosion in RC made from treated RCA and modification of the microstructure.
- Regulations governing the incorporation of properly treated RCA.

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