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Review Article

Durability Studies on the Recycled Aggregate Concrete in China over the Past Decade: A Review

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Since China hosted the Olympic Games in 2008, a mass of construction and demolition (C&D) wastes were produced with the rapid urbanization construction. Recycling the C&D waste into recycled aggregates (RA) is an effective method for reducing the amount of C&D wastes. Many studies on the properties of RA and the durability of recycled aggregate concrete (RAC) were conducted in China over the past decade. Due to the restrictions of various languages, some valuable studies on the durability of RAC are hard to be acquired by the scholars around the world. Therefore, this paper is developed to review the studies on the durability of RAC in China, and the shrinkage behavior, chloride permeability, carbonation behavior, and freeze-thaw resistance of RAC are, respectively, introduced. Considering the waste concrete, bricks, and ceramics used in preparing RA are frequently mixed together in China, this study proposes an index of average water absorption rate to quantify the effects of RA types, quality, and replacement percentages on the durability of RAC. Meanwhile, the relationship between the average water absorption rate of RA and the durability parameters of RAC is established. Finally, the improving methods of RAC durability are introduced, and the RA particle shaping and carbonation modification are emphasized.

1. Introduction

With the rapid development of construction industry, large amounts of construction and demolition (C&D) wastes are being produced [1, 2]. The disposal of such wastes at air storage or landfills inevitably produces some environmental problems (such as soil, water, and air pollution) because C&D wastes may contain some hazardous substances [3–5]. Thus, researchers around the world aim to develop the recycling technology of C&D wastes to reduce the amount of C&D wastes, and meanwhile, the recycled materials can be further used as the building materials in the new construction projects [6, 7]. At the present stage, the C&D wastes are frequently used to produce the recycled aggregates (RA), which include the recycled fine aggregate (RFA) and recycled coarse aggregate (RCA). Furthermore, recycled aggregate concrete (RAC) can be prepared by replacing the natural aggregates (NA) with RA in concrete [8, 9].

In 2008, it was well known that Beijing Olympic Games was successfully hosted by China, and an ultrarapid urbanization was witnessed over the past decade, which resulted in the production of a mass of C&D wastes. At the same year, a magnitude-8 earthquake happened in Wenchuan of China, and massive C&D wastes were produced and urgent to be disposed [10]. In this case, Chinese government attached high attention to the recycling of C&D wastes, and increasing numbers of research projects were funded by the National Natural Science Foundation of China.

The C&D wastes in developed country (such as Japan) are mainly composed of single waste concrete, which is easy to be recycled, and the produced RA generally has good properties [11]. Distinguishing with the C&D wastes in developed country, the C&D wastes in China are frequently mixed together and contain a mass of waste concrete, waste bricks, and waste ceramics [12]. Especially for the demolition wastes, its components are more various. Using multi-component C&D wastes to produce RA inevitably results in the inferior properties of prepared RAC, which limits the wide application of RA and RAC. Thus, the studies on the properties of RA and RAC in China should be distinctively focused.

A great number of studies have been carried out on the microstructure characteristics [13], mechanical properties [14], durability performance [15], and structural safety [16] of RAC to ensure its safety use in construction industry. Particularly, the results highlight that the addition of RA plays a negative impact on the durability of concrete. The water permeability [17], chloride permeability [18], sulfate attack [19], carbonation behavior [20], and freeze-thaw resistance [21] of RAC have been extensively investigated in recent years, and the results demonstrate that the durability deteriorates with the alterative use of RA, and the deterioration becomes more significant with the increase of RA content in concrete. More recently, some review articles [22–24] have introduced the previous findings on the durability of RAC, and some valuable suggestions were given, whereas the published literatures in Chinese were less cited in these review studies due to the limitation of the language. Moreover, in view of the complex properties of RA in China, the effects of RA types and quality on the durability of RAC were less considered in the previous studies.

Thus, this paper is developed to better understand the influence of RA on the durability of RAC in China. The related Chinese literatures on the properties of RA and the durability of RAC are reviewed in detail, and the improvement method of RAC durability is further introduced. In China, various types of RA are frequently mixed together, and the properties of RA obtained from various C&D wastes are quite different. Thus, this paper proposes an index of average water absorption rate which is related to the replacement percentages and quality of RA to quantify the effects of RA properties on the durability of RAC. Furthermore, the relationship between the durability parameters of RAC and the average water absorption rate of RA is established in this study. We hope the related investigations on the durability of RAC in China can be well acquired by the scholars around the world, and some suggestions in this study may be helpful for the further investigations on the durability of RAC.

2. Characteristics of Recycled Aggregates in China

2.1. C&D Wastes and Its Recycling Technology. In China, the rapid urbanization which reaches to about 58.5% in 2017 results in a massive construction of the new building along with the demolition of the old building [25, 26]. Figure 1 gives the output of C&D wastes from 2008 to 2017 in China, and the results show that the amount of C&D wastes generally increases with increasing years, and it is, respectively, 1.6 and 1.8 billion tons in 2016 and 2017 [27]. For effectively reducing the amount of C&D wastes in China, the recycling technology and related studies on the C&D wastes were conducted. Figure 1 further gives the number of

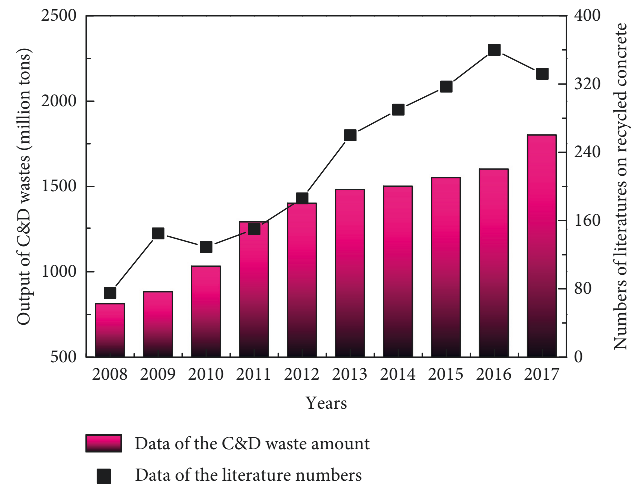


Figure 1: Output of C&D waste and the related literatures in China over the past decade.

literatures on RAC from 2008 to 2017 by searching the keyword of “recycled concrete” in CNKI, which shows that the number of literature studies is on the rise in recent ten years [28].

The properties of RA obtained from various sources of C&D wastes are quite different [29–34]. The brick-concrete structure which accounts for above 60% of the whole buildings is the most common building type in the town of China, which is quite different from the developed countries in which the reinforced concrete structure is the main building type [35, 36]. Thus, the properties of RA in China are much different from those in the developed country, and the RA produced by the waste concrete, waste bricks, and waste ceramics is frequently mixed together, whereas the RA in many developed countries is almost the recycled concrete aggregate [11, 37, 38]. Table 1 gives the compositions of the C&D wastes in a typical city of China. Although the compositions of the construction wastes and demolition wastes are quite different, the waste concrete, waste bricks, and waste ceramics are the main compositions, which account for above 80% of the whole C&D wastes. Thus, the recycled concrete aggregates, recycled brick aggregates, and recycled ceramic aggregates are the most common types of RA in China.

2.2. Characteristics of Recycled Aggregates. The characteristics of RA are closely related to the properties of prepared RAC. This section collects the related research results of RA properties in China, and they are described in Table 2 [41–55]. For the RA produced by waste concrete, its average water absorption is about 4.55%, and its average crushing index and average apparent density are, respectively, 21.5% and 2627 kg/m^3 [41–46]. Particularly, Xiao et al. [41] found that the strength of original concrete had a significant impact on the properties of produced RA, and the higher strength of original concrete resulted in the better properties of produced RA.

Table 1: Compositions of C&D wastes in a typical city of China [39, 40].

Waste types	Compositions (%)				
	Concrete	Brick	Gypsum	Steel	Wood
Construction wastes	42.9	38.3	1.1	6.5	11.2
Demolition wastes	22.6	63.8	2.1	3.1	8.4

Table 2: Physical properties of RA obtained from various sources.

Sources of RA	References	Water absorption (%)	Crushing index (%)	Apparent density (kg/m^3)
Waste concrete	Original concrete strength: C20 [41]	4.8	27.26	—
	Original concrete strength: C30 [41]	4.7	23.77	—
	Original concrete strength: C40 [41]	4.35	22.99	—
	Original concrete strength: C50 [41]	3.25	19.78	—
	[42]	4.75	14.30	—
	[43]	5.63	15.00	2600
	[44]	4.55	32.00	2630
	[45]	5.70	24.80	2690
	[46]	3.26	13.20	2587
Waste brick	[47]	14.13	38.00	2245
	[48]	21.80	29.93	1652
	[49]	13.81	34.47	2461
	[50]	16.30	30.00	1610
Waste ceramics	[51]	1.50	6.70	2398
	[52]	3.84	6.97	2380
	[53]	3.31	6.20	2375
	[54]	2.93	7.30	2380
	[55]	3.31	7.90	2375

For the RA obtained from waste brick, its average water absorption, average crushing index, and average apparent density are, respectively, 16.51%, 33.1%, and 1992 kg/m^3, as shown in Table 2 [47–50]. In addition, the chemical composition and microstructure of recycled brick aggregates are quite different from those of recycled concrete aggregates, and the high porosity of recycled brick aggregates should be carefully considered in the mix design and concrete preparation. For the RA obtained from waste ceramics, the average water absorption, average crushing index, and average apparent density are, respectively, 2.98%, 7.01%, and 2381.6 kg/m^3 [51–55]. Comparing with the results reported above, the recycled brick aggregates have the highest water absorption, and meanwhile, the recycled ceramic aggregates have the lowest water absorption. For example, the average water absorption of recycled brick aggregates and recycled ceramic aggregates are, respectively, 3.63 times and 65% as high as those of recycled concrete aggregates.

The water absorption, crushing index, and apparent density are all the important parameters of RA properties, and Figure 2 gives the relationship between them. The results show that the apparent density decreases linearly with the increase of water absorption, whereas the crushing index increases linearly with increasing water absorption. Therefore, the water absorption is an appropriate indicator to quantify the properties of RA which may be obtained from various types and sources of C&D wastes. Considering the properties and replacement percentages of RA in various literatures are quite different, this study further proposes an index of average water absorption rate to quantize the properties of RA. The specific equation is described in the following:

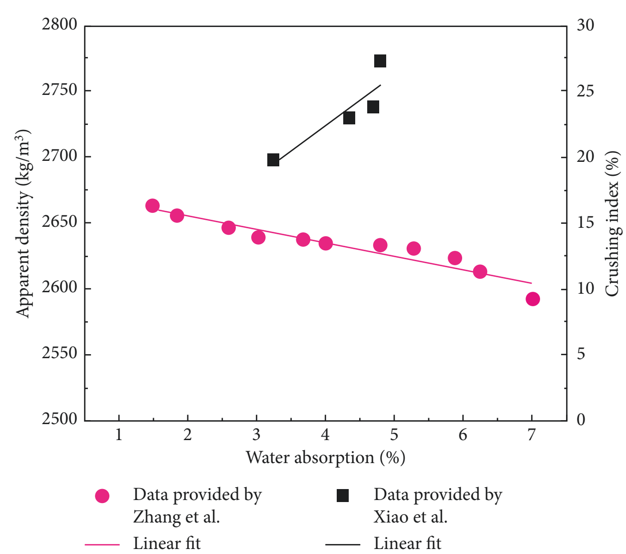


Figure 2: Relationship between the water absorption and apparent density or crushing index of RA [41, 43].

$$A_{\mathrm{Avg}} = A_{\mathrm{NA}} \times p\% + A_{\mathrm{RA}} \times (100 - p\%), \quad (1)$$

where A_{Avg} is the average water absorption rate of RA or a mixture of NA and RA (%), the A_{NA} and A_{RA} are the water absorption of NA and RA (%), and p presents the replacement percentages of NA (%).

3. Durability Properties of Recycled Aggregate Concrete in China

3.1. Shrinkage Behavior of RAC. The shrinkage behavior is closely related to the durability properties of concrete, and it is an important index of concrete durability according to the Chinese standard "Standard for test methods of long-term performance and durability of ordinary concrete" (GB50082-2009) [56]. Figure 3 collects the testing results of the shrinkage behavior of RAC [55–70], and it gives the correlation between the relative shrinkage value of RAC and the replacement percentages or average water absorption rate of RA. The results highlight that the increasing RA content and average water absorption rate both result in an increase in the relative shrinkage value of RAC. Particularly, the increase in the relative shrinkage value becomes more obvious for the RA with a high average water absorption rate, which manifests that the shrinkage behavior is significantly impacted by the quality of RA. Luo et al. [71] further found that the shrinkage behavior of RAC decreases with the increase of RA quality.

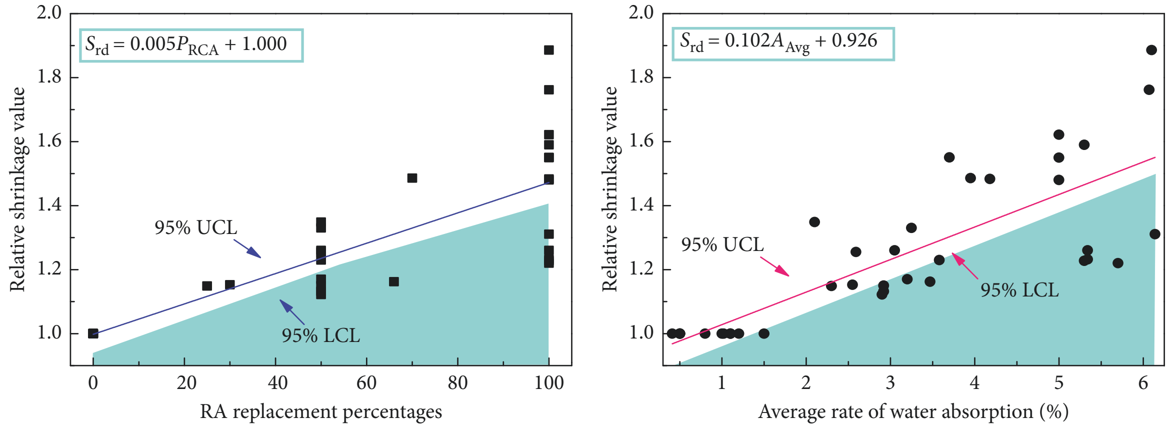
The results by the previous investigations highlight that the addition of RA plays a negative effect on the shrinkage behavior of concrete. Wang [57] found that the elasticity modulus of RA had an obvious impact on the shrinkage behavior of concrete. The relative low elasticity modulus of RA reduces the restraining function on the shrinkage of new mortar, and meanwhile, the shrinkage strain is happening in RA, which increases the shrinkage behavior of RAC. In addition, a mass of initial damage (such as cracks and flaws) are existed in the adhered old mortar and ITZ of RA because the RA is produced by the mechanical crushing of C&D wastes. Wang [60] found that the initial damage of RA was a leading reason that RAC had the higher shrinkage behavior than NAC. The initial damage of RA increased the pore water content of concrete, and the water loss rate was increased, which resulted in a rapid decrease in the relative humidity of RAC and then the shrinkage behavior increased. Furthermore, the difference between the shrinkage behavior of RAC and NAC becomes more significant with the increase of curing time [72], and the impacts of RA on the shrinkage behavior are more obvious for the high-performance concrete with RA [73].

It can be seen from Figure 3 that the relative shrinkage value increases linearly with the increase of RA content and the average water absorption rate. The specific equations are also described in Figure 3, where $S_{\mathrm{rd}} = S_{\mathrm{RAC}}/S_{\mathrm{NAC}}$ is the relative shrinkage value and the S_{RAC} and S_{NAC} are the shrinkage value of RAC and NAC, %. The shrinkage value of RAC with 100% RA replacement percentages is about 1.5 times as high as that of NAC, and the shrinkage value of RA with 6% water absorption rate is about 0.57 times higher than that with 0.5% water absorption rate. Furthermore, Figure 4 gives the correlation among the shrinkage behavior of RAC, average water absorption rate, and replacement percentages of RA. When the average water absorption rate is the same or RA has the similar properties, the relative shrinkage value increases with the increase of RA replacement percentages. In contrast, when the RA replacement percentages are the same, the relative shrinkage value increases with the increase of average water absorption rate.

3.2. Chloride Permeability. Chloride permeability is the leading reason that results in the steel corrosion of reinforced concrete, and the chloride permeability is frequently quantified by the values of chloride diffusion coefficient which can be obtained by Fick's second law [74, 75]. Chinese scholars have systematically investigated the chloride diffusion behavior of RAC, and Figure 5 collects testing results of relative chloride diffusion coefficient of RAC [69, 76–88]. The results manifest that the increasing RA content and average water absorption rate increase the chloride diffusion coefficient. By fitting the data in Figure 5, it is noted that the relative chloride diffusion coefficient increases linearly with the increase of RA content and average water absorption rate, whereas the discreteness in Figure 5(b) is lower than that in Figure 5(a).

The specific equations are also described in Figure 5, where the $D_{\mathrm{rd}} = D_{\mathrm{RAC}}/D_{\mathrm{NAC}}$ is the relative chloride diffusion coefficient and the D_{RAC} and D_{NAC} are, respectively, the chloride diffusion coefficient of RAC and NAC, $10^{-12}\,\mathrm{m}^2/\mathrm{s}$. As shown in Figure 5(a), the relative chloride diffusion coefficient of concrete with 100% RA replacement percentages is about 0.5 times higher than that of NAC. Obtaining from Figure 5(b), the chloride diffusion coefficient of RA with 6% average water absorption rate is about 1.67 times as large as that with 0.5% average water absorption rate. Moreover, Shen et al. [89] discovered that the addition of RA boosted the steel corrosion risk of reinforced concrete, and Zhang [90] presented the steel corrosion model of reinforced recycled concrete, and he found that the cracks caused by steel corrosion were easy to form along the old and new ITZs of RAC.

The results above show that RAC has a higher chloride permeability than NAC, and the chloride diffusion coefficient increases with the increase of RA replacement percentages. On the one hand, the inferior properties of RA with massive initial damage lead to an increase in the total porosity of concrete, which provides more paths for chloride penetration into RAC; on the other hand, the old and new ITZs between aggregates and mortar are loose, and some obvious cracks can be observed on them, which further reduces the resistance to chloride permeability [91, 92]. Tan and Yang [93] obtained that the chloride diffusion coefficient of ITZ on RA was about 5 times higher than that on NA through a chloride diffusion test on a modelling RAC sample. Combining with the method of numerical modelling and theoretical calculation, Wei [94], Ying et al. [95], and Xiao et al. [96] proposed that the RAC can be seemed as a five-phase composite materials which included the NA, old ITZ, old mortar, new ITZ, and the new mortar, and they found that the old mortar content and its properties were the



(a) (b)

FIGURE 3: Shrinkage behavior of concrete with (a) various RA contents and (b) various water absorption rates [57–70].

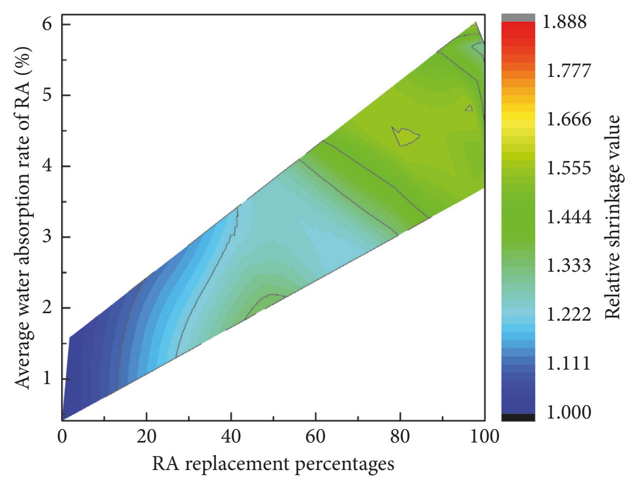
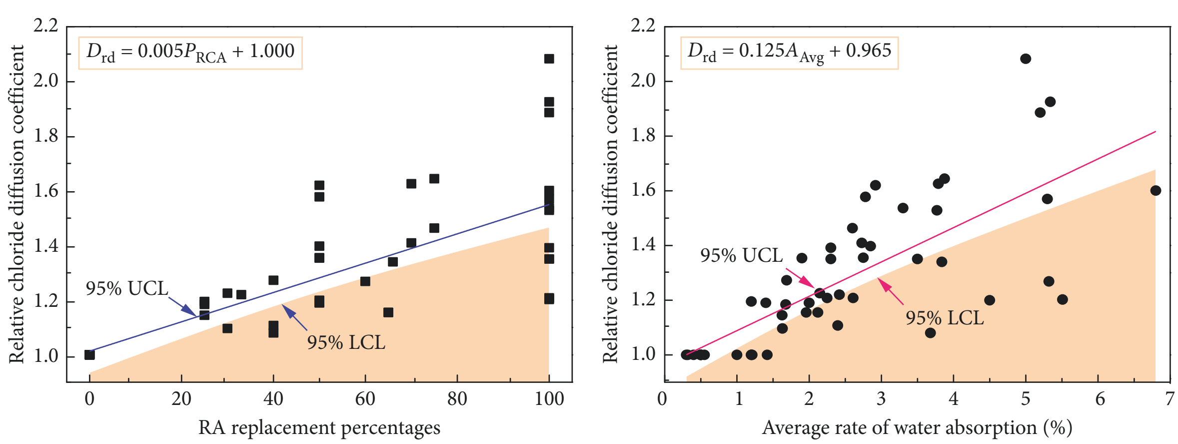


FIGURE 4: Correlation between the shrinkage behavior of RAC, average water absorption rate, and replacement percentages of RA.



(a) (b)

FIGURE 5: Chloride permeability of concrete with (a) various RA contents and (b) various average water absorption rates [69, 76–88].

leading influencing factor that affected the chloride permeability. It is worth noting that there are a mass of RA obtained from waste fired brick in China, and the recycled brick aggregate has a porous structure, and thus, the addition of recycled brick aggregates significantly boosts the porosity and the chloride permeability of concrete [97–99].

Figure 6 gives the correlation among the relative chloride diffusion coefficient, average water absorption rate, and RA replacement percentages. The results highlight that the RA replacement percentages and the average water absorption rate both have an obvious impact on the chloride permeability. When the RA has the same average water absorption rate or has the similar properties, the chloride permeability generally increases with the increase of RA content. In contrast, when the RA replacement percentages are the same, the chloride permeability increases with the increase of average water absorption rate.

3.3. Carbonation Behavior. Carbonation reduces the alkali content of concrete and increases the steel corrosion risk of reinforced concrete, and it is an important indicator of concrete durability [100, 101]. Figure 7 summarizes the results of carbonation behavior of RAC [54, 69, 70, 77, 102–113]. The results highlight that the increasing RA content and average water absorption rate result in an increase in the relative carbonation depth of RAC. By fitting the data, the relative carbonation depth increases linearly with the rise of RA content and its average water absorption rate. It can be seen from Figure 7(a) that the carbonation depth for RA with 6% water absorption rate is about 1.75 times as high as that for NA with 0.5% water absorption rate. The specific equations are described in Figure 7, where $C_{\mathrm{rd}} = C_{\mathrm{RAC}}/C_{\mathrm{NAC}}$ is the relative carbonation depth and the C_{RAC} and C_{NAC} are the carbonation depth of RAC and NAC, mm. It is worth noting that the discreteness in Figure 7(b) is lower than that in Figure 7(a), which highlights that the average water absorption rate is an appropriate index to evaluate the carbonation behavior of RAC.

The results above show that the addition of RA has an obvious impact on the carbonation behavior of RAC. There are a mass of initial damage on RA, and the total porosity of concrete increases with the increase of RA content, which provides more paths for CO_2 gas penetrating into RAC and increases its carbonation behavior. Sun et al. [114, 115] found that the gas permeability of concrete with 60% RA replacement was about 1.96 times as high as that of NAC, and the carbonation depth of RAC was about 0.75 times higher than that of NAC Meanwhile, the mortar content of concrete increases with the increase of RA replacement percentages, which is helpful to improve the carbonation resistance [109]. Although the addition of RA has two opposite impacts on the carbonation behavior of concrete, the adverse effect generally plays a leading role. Especially for the porous recycled brick aggregates without adhered old mortar, the carbonation behavior significantly increases with the increase of RA replacement percentages.

Considering the RAC is inevitably subjected to the loading condition, Xiao and Lei [116] proposed a carbonation model to predict the carbonation depth of RAC with various applied loads. The specific equation is shown in the following:

$$x_{\mathrm{c}} = k_{\mathrm{CO_2}} k_{\mathrm{k1}} k_{\mathrm{ks}} T^{0.25} R^{1.5} (1 - R) \left(\frac{230}{f_{\mathrm{cu}}^{\mathrm{RC}}} + 2.5 \right) \sqrt{t}, \tag{2}$$

$$\begin{aligned} x_{\mathrm{c}} &= k_{\mathrm{RA}} k_{\mathrm{CO_2}} k_{\mathrm{k1}} k_{\mathrm{ks}} T^{0.25} R^{1.5} (1 - R) \left(\frac{270.14}{f_{\mathrm{cu}}^{\mathrm{RC}}} - 7.52 \right) \sqrt{t}, \\ &\qquad P_{\mathrm{RA}} \leq 50\%, \\ x_{\mathrm{c}} &= k_{\mathrm{RA}} k_{\mathrm{CO_2}} k_{\mathrm{k1}} k_{\mathrm{ks}} T^{0.25} R^{1.5} (1 - R) \left(\frac{342.89}{f_{\mathrm{cu}}^{\mathrm{RC}}} - 8.65 \right) \sqrt{t}, \\ &\qquad P_{\mathrm{RA}} > 50\%. \end{aligned} \tag{3}$$

where x_{c} is the carbonation depth of RAC (mm); $k_{\mathrm{CO_2}} = \sqrt{C_0/0.2}$ is the influence coefficient of CO_2 concentration; C_0 is the volume concentration of CO_2; k_{k1} presents the influence coefficient of location, which is 1.4 and 1.0 at the corner region and the other regions of sample; k_{ks} is the influence coefficient of applied stress, and it is 1.0 and 1.7 with compressive loading and tensile loading; T is the environment temperature; and $f_{\mathrm{cu}}^{\mathrm{RC}}$ is the compressive strength of RAC. But this model did not take the effects of RA replacement percentages into consideration. Huang [117] further updated this model based on the testing results, and the new model had relative high prediction accuracy. The detained equation is described in equation (3), where the k_{RA} is the influence coefficient of RA replacement percentages and it can be obtained from Table 3.

Figure 8 gives the correlation among the relative carbonation depth of RAC, the replacement percentages, and average water absorption rate of RA. When the RA replacement percentages are the same, the relative carbonation depth increases with the increase of average water absorption rate, whereas when the average water absorption rate of RA is the same, the relative carbonation depth boosts with the increase of RA replacement percentages, and the carbonation behavior significantly increases when the replacement percentages of RA are above 60%.

3.4. Freeze-Thaw Resistance. Exposing to the cold condition, the concrete is inevitably subjected to the condition of freeze-thaw cycles, and the induced freeze-thaw damage reduces the mechanical and durability properties of concrete [118–120]. The mass loss and relative dynamic elastic modulus (E_{rd}) are two important indicators of freeze-thaw resistance of concrete [121]. Figure 9 collects the data of mass loss of RAC [69, 76, 77, 122–131]. The results show that the relative mass loss generally increases linearly with the increase of RA content and average water absorption rate. For example, the relative mass loss of RAC with 100% RA replacement is about 1.1 times higher than that of NAC, and the mass loss for RA with 6% water absorption rate is about 1.5 times higher than that with 0.5% water absorption rate. However, comparing with the results in Figures 9(a) and 9(b), the discreteness in Figure 9(b) is much lower than that

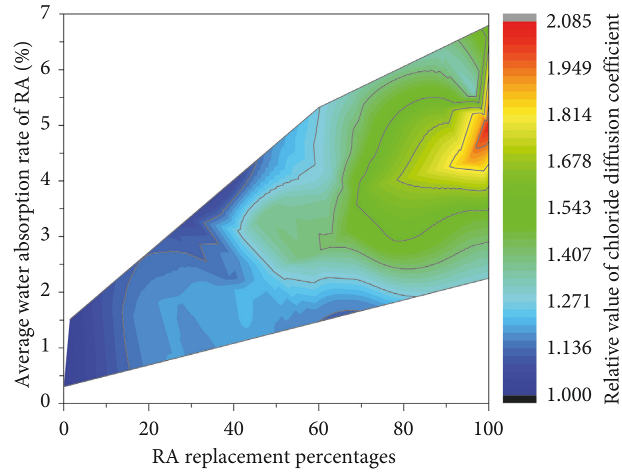


FIGURE 6: Correlation between the relative chloride diffusion coefficient of RAC, average water absorption rate, and replacement percentages of RA.

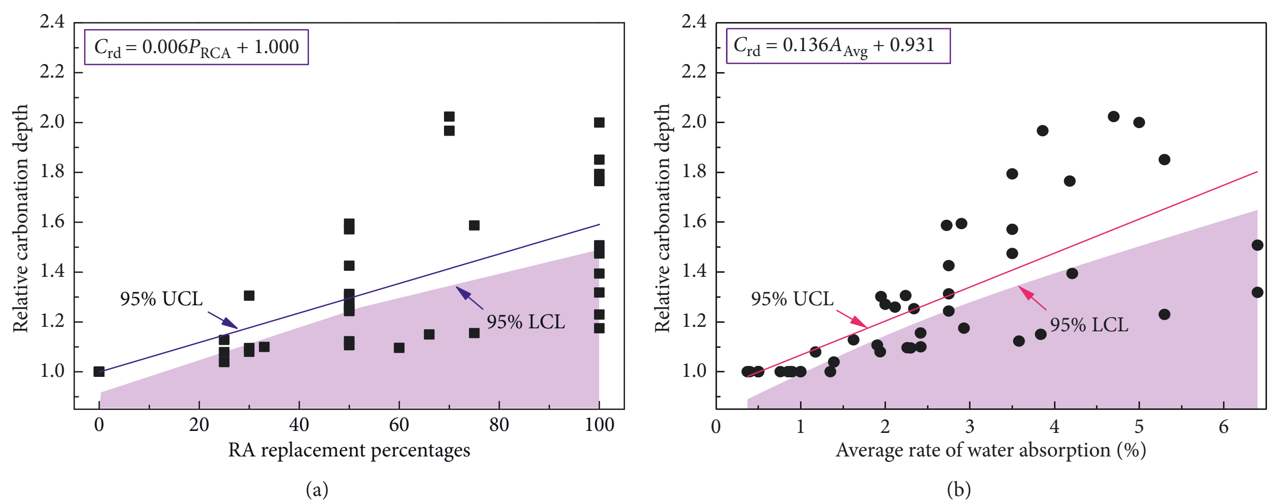


FIGURE 7: Carbonation behavior of RAC with (a) various RA contents and (b) various average water absorption rates [54, 69, 70, 77, 102–113].

TABLE 3: Reference value of k_{RA} with various RA replacement percentages [117].

w/c	30%	50%	70%	100%
0.45	1.0	1.0	0.9	0.8
0.55	1.0	0.9	1.0	0.9
0.65	1.0	1.1	1.0	1.2

in Figure 9(a), which demonstrates that the index of average water absorption rate is more suitable to estimate the freeze-thaw resistance of RAC with various types and replacement percentages of RA.

Figure 10 collects the relative E_{rd} of RAC by the published literatures. The results highlight that the relative E_{rd} of RAC decreases with the increase of RA content and its average water absorption rate. By fitting the data, it is found that they follow a linear relation, and the discreteness and fitting error in Figure 10(b) are lower than that in Figure 10(a). The specific is also described in Figure 10, where the $E_{rd} = E_{rd,RAC}/E_{rd,NAC}$ is the relative value of relative dynamic elastic modulus and the $E_{rd,RAC}$ and $E_{rd,NAC}$ are the relative dynamic elastic modulus of RAC and NAC, %. The results above manifest that the freeze-thaw resistance of concrete reduces with the increase of RA content and average water absorption rate. For example, the E_{rd} of concrete with 100% RA replacement is about 80% as high as that of plain concrete, and the E_{rd} for RA with 6% average water absorption rate is about 81% as high as that with 0.5% average water absorption rate.

Chen et al. [134] and Wu and Zhu [135] found that the low freeze-thaw resistance of RAC was mainly caused by the existence of multiple interfaces between aggregates, old mortar, and new mortar. There are massive cracks and pores on the adhered old mortar and ITZ of RA, which increases the water absorption of concrete. Subjecting to the condition of freeze-thaw cycles, the higher water absorption results in the higher freeze-thaw expansion stress, which increases the mass loss and decreases the E_{rd} of RAC. Wu et al. [135] and

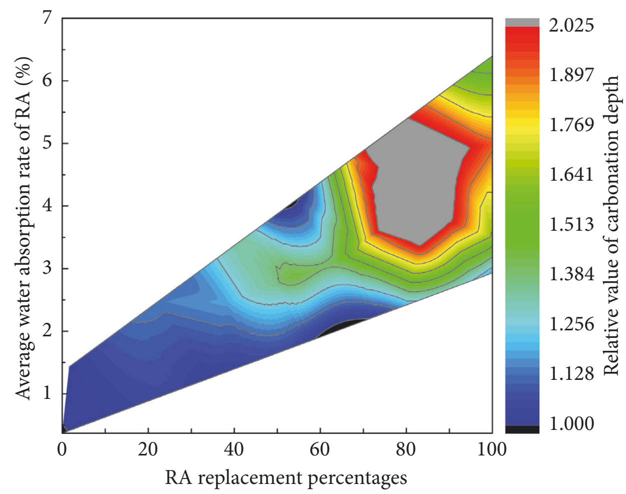


Figure 8: Correlation between the relative carbonation depth of RAC, the average water absorption rate, and replacement percentages of RA.

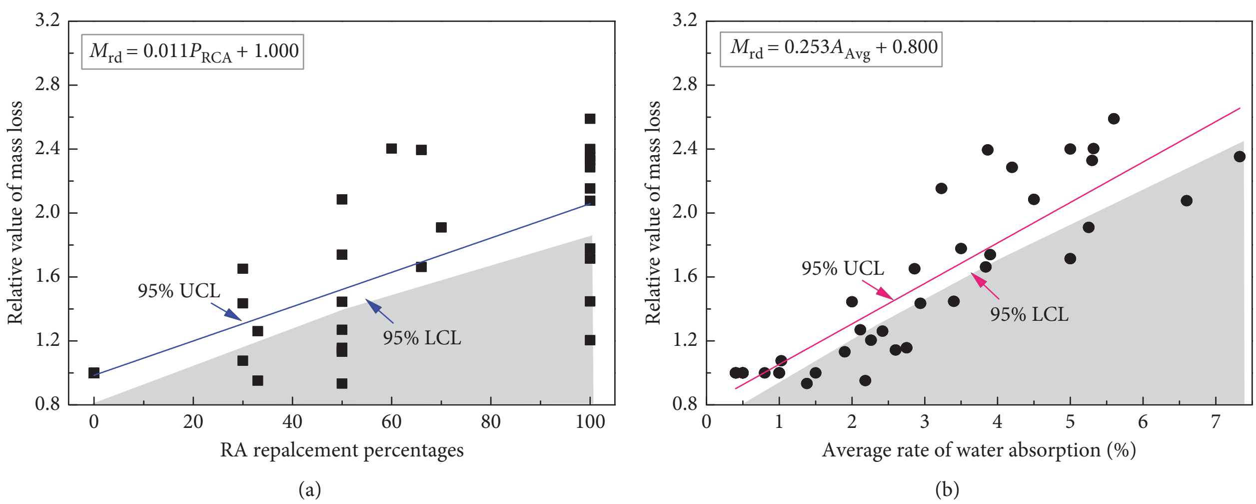


Figure 9: Mass loss of concrete with various contents and average water absorption rate of RA [69, 76, 77, 122–131]. (a) Effects of replacement percentages. (b) Effects of average water absorption rate.

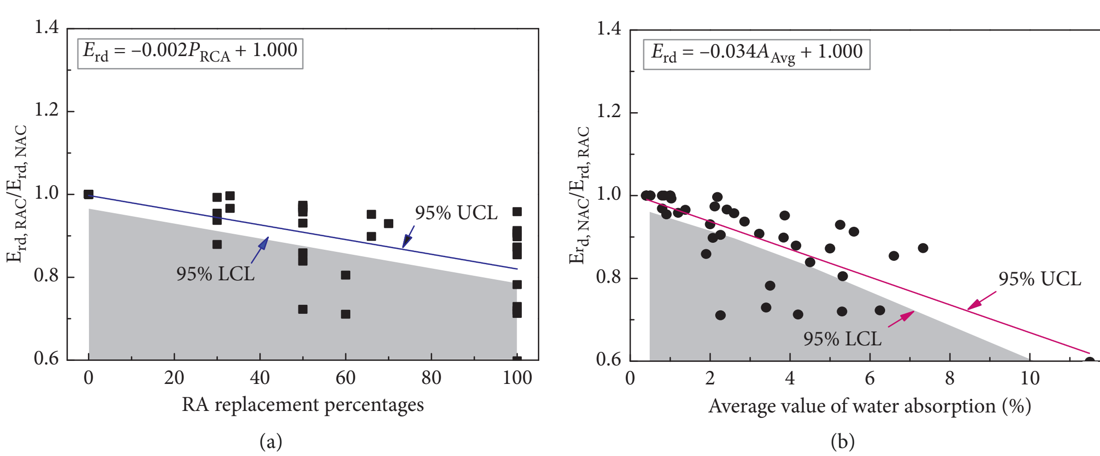


Figure 10: Relative dynamic elastic modulus of concrete with (a) various contents and (b) various average water absorption rates of RA [69, 76, 77, 113, 122–128, 132, 133].

Chen et al. [136] found that the freeze-thaw resistance of RAC can be improved by reducing the water saturation of RA. Zhang et al. [137] and Chen et al. [138] explained that the addition of RA increased the porosity of concrete, and the increased porosity resulted in a decrease in the freeze-thaw resistance. Meanwhile, the freeze-thaw resistance is obviously impacted by the quality of RA, and the addition of low-quality RA further reduces the freeze-thaw resistance due to the poor properties of adhered old mortar and ITZ on RA.

Figure 11 gives the correlation among the freeze-thaw resistance of RAC, average water absorption rate, and replacement percentages of RA. The results manifest that the increased replacement percentages and average water absorption rate of RA both result in an increase in the mass loss and a decrease in the E_{rd} of RAC under the condition of freeze-thaw cycles. When the average water absorption coefficient of RA is the same, the addition of RA reduces the freeze-thaw resistance of RAC. In addition, the freeze-thaw resistance of concrete decreases with the increase of average water absorption rate of RA when its replacement percentages are the same.

3.5. Other Durability Properties. Aggressive ions penetration into concrete is mainly by the medium of water penetration, and the water permeability is also an important indicator of concrete durability [139, 140]. Ding et al. [141] investigated the water permeability of RAC by a capillary absorption test, and the results demonstrated that the adding RA increased the water permeability of concrete; such as, the absorbed water amount of concrete with 100%, 50%, and 30% RA replacement was, respectively, 1.52, 1.39, and 1.32 times as high as that of NAC. Zong et al. [142] and Zhang and Wang [143] further studied the water permeability of RAC with the application of hydrostatic pressure, and they found that 30% of RA replacement leaded to the depth of water penetration increased by 25%.

When concrete subjects to the marine environment, it frequently suffers the sulfate attack, and the concrete failure happens along with a serious surface scaling and inner damage [144]. Although the studies on the sulfate attack of RAC are less, some general conclusions can be drawn by the scholars in China. Fu et al. [145], Yan et al. [146], and Tao et al. [147] all found that the addition of RA boosted the induced damage of sulfate attack, which was attributed to that the addition of RA increased the initial damage and more corrosion products were produced. Additionally, the multiple interfaces of RAC also aggravated the performance degradation of RAC under sulfate attack [148]. An et al. [149, 150] also obtained the similar conclusions, and they further established the damage model of RAC under sulfate attack. The detailed equation is described in the following:

$$D_{\mathrm{N}} = 1 - \alpha k_1 k_2 k_3 \left[g N^2 + h N + 1 \right], \tag{4}$$

where D_{N} is the cumulative damage of RAC, N is the wet-dry cycles of sulfate, α with the value of 1.0 is the variation coefficient, $k_1 = -0.0038 S_{\mathrm{l}}^2 + 0.0265 S_{\mathrm{l}} + 0.9612$ presents the correction coefficient of solution concentration (S_{l}), $k_2 = 1.0177 e^{-0.0002 r}$ is the correction coefficient of RA content (r), and $k_3 = 0.9207 e^{0.0026 f_{\mathrm{cu,0}}}$ is the correction coefficient of RA strength ($f_{\mathrm{cu,0}}$), $g = -9.0375 \times 10^{-5}$, and $h = 5.5126 \times 10^{-3}$.

The abrasion frequently leads to the surface defect of concrete and reduces its strength; therefore, the abrasive resistance is also an important indicator of concrete durability [151]. Chen [152] and Shi et al. [153] both found that the addition of RA reduced the abrasive resistance of concrete, and the decrease was slight when the RA replacement percentages were below 50%, whereas it became more significant when the RA replacement percentages were above 50%. For example, the abrasion loss of RAC with 50%, 75%, and 100% of RA replacement, respectively, increased by 1.1%, 14.7%, and 23.4% compared with that of NAC. Yang et al. [154] obtained the similar conclusion and found that the abrasion loss of concrete increased by 0.4% and 30.9% when the RA replacement percentages were, respectively, 40% and 100%. The addition of RA reduces the strengths of concrete, and the lower strengths resulted in the higher abrasion loss of concrete [155]. Furthermore, the inferior properties of RA further increased the abrasion loss of concrete because a mass of cracks and flaws were existed in the adhered old mortar and ITZ of RA [156].

4. Improvement Methods of Durability

The addition of RA has a negative impact on the concrete durability. Therefore, the improvement methods are developed in recent years, and the RA (mainly the recycled concrete aggregate) and RAC after modification have the better microstructure behavior and durability performance than that without modification [157–159]. Removing and enhancing the adhered old mortar of RA are two main methods to improve the durability of RAC in China.

4.1. Removing the Adhered Old Mortar of RA. Xiao et al. [160] first proposed the method of microwave heating to remove the adhered old mortar on RA. With the application of microwave on RA, the surface temperature of RA instantly reaches around 300°C, whereas the inner temperature is still low. In this case, a thermal stress is produced by a significant temperature difference between the inner and surface of RA, which results in the spalling of adhered old mortar from RA. The results found that the treatment of microwave heating can remove above 50% of adhered old mortar of RA, which led to the water absorption of RA decreased by about 28.4% and the durability can be improved. Furthermore, the combination technology of microwave heating and mechanical crushing is developed to improve the efficiency of RA modification [161].

As shown in Figure 12(a), Li et al. [162, 163] invented a particle shaping equipment that can effectively remove the adhered old mortar of RA, and this equipment had been widely applied in the RA modification in China. The ordinary RA was first accelerated to the speed of 100 m/s by a projecting disc, and then, the adhered old mortar can be removed by the striking between various RA with a high speed. In addition, the properties of modified RA are

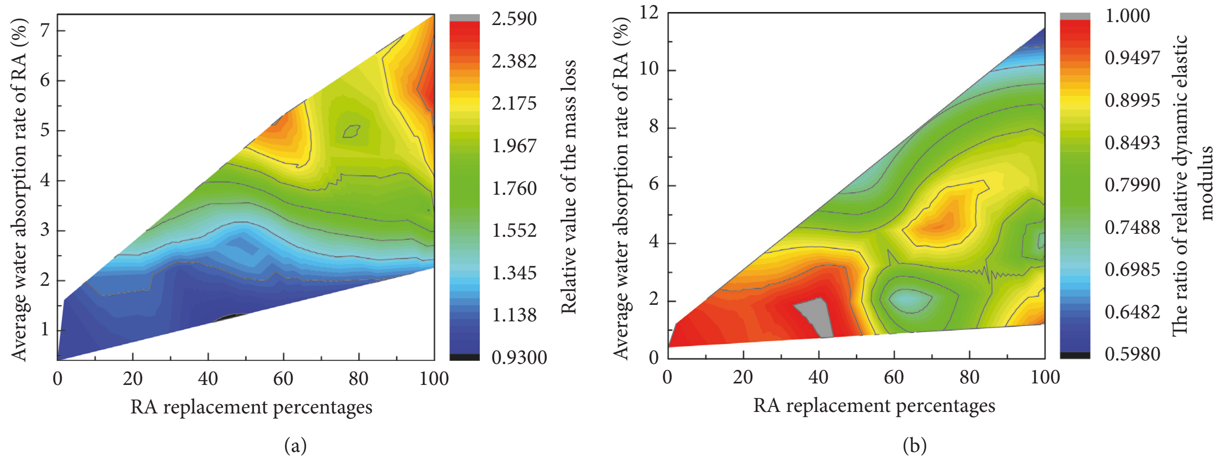


Figure 11: Correlation between the freeze-thaw resistance of RAC, average water absorption rate, and replacement percentages of RA. (a) Mass loss and (b) relative dynamic elastic modulus.

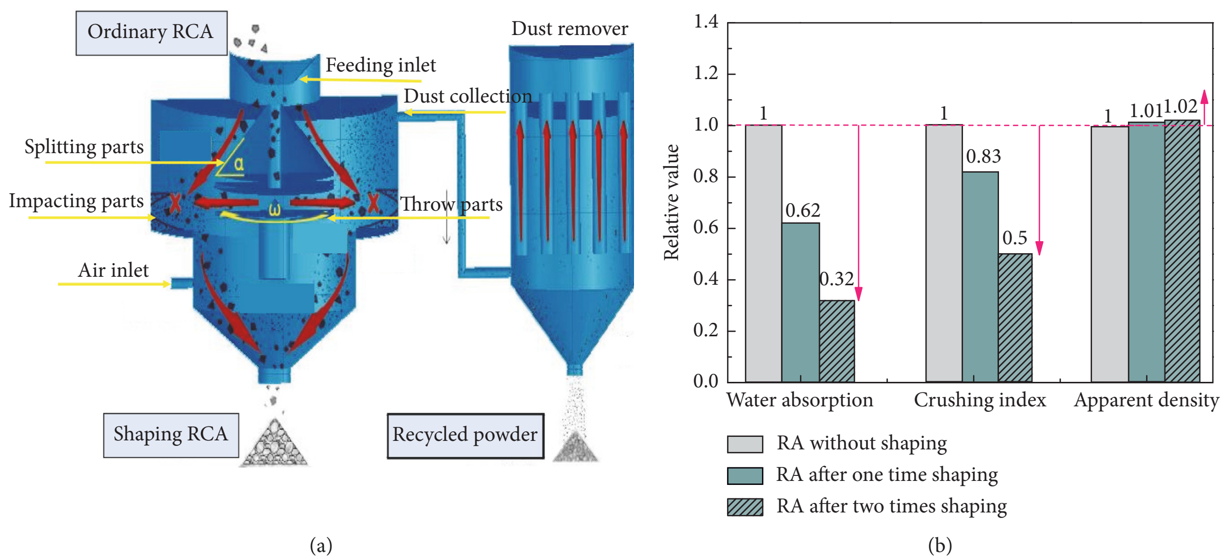


Figure 12: Fundamental characteristics of RCA with and without shaping. (a) Particle shaping equipment [162, 163]. (b) Properties of RA after various shaping cycles [164].

increased with the increase of shaping cycles, and Figure 12(b) gives the characteristics of RA after various shaping cycles [164]. The water absorption of RA after one and two shaping cycles is, respectively, about 62% and 32% of that without shaping treatment, and the results become 83% and 50% for the crushing index. The modified RA is the main products, and meanwhile, the recycled powder is the by-product, and it can be used as the binding materials to partially replace the cement in concrete [165, 166]. After few shaping cycles, above 90% of adhered old mortar on RA can be removed, and the quality of RA can reach the properties of NA [167–169].

Figure 13 further collects the durability parameters of concrete with shaping RA. The results highlight that the shrinkage rate of concrete with RA after one and two shaping cycles is, respectively, 95% and 87% of that with untreated RA [170], and the results become 86% and 73% for the chloride diffusion coefficient [171] and the results are 69% and 56% for the carbonation depth [172]. Moreover, the freeze-thaw resistance of concrete with RA after one and two shaping cycles increases by 37% and 109% compared with that with untreated RA [172]. Because the treatment of RA particle shaping can effectively reduce the content of adhered old mortar and correspondingly decrease the initial damage of RA, the increased quality of RA improves the durability of RAC [173, 174].

4.2. Enhancing the Adhered Old Mortar of RA. Enhancing the adhered old mortar of RA is also an effective method to improve its properties. Ding et al. [175] and Li et al. [176] found that the properties of RA after presoaking in a cement paste were improved, and the improvement of freeze-thaw resistance was more obvious. Zhu et al. [177] and Yang et al.

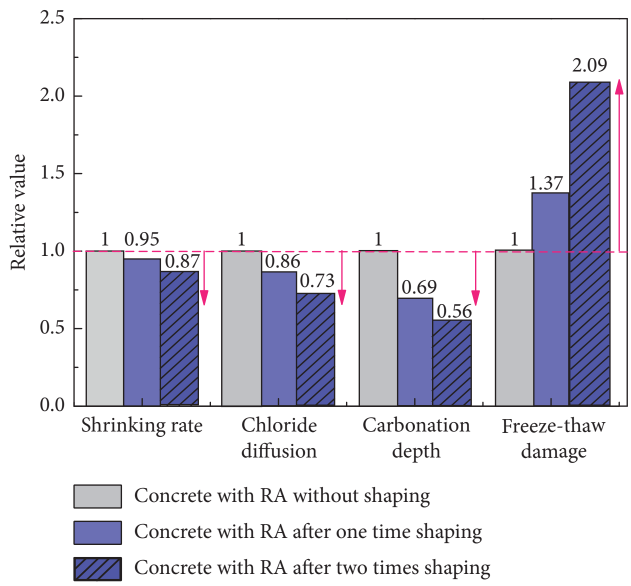


FIGURE 13: Durability properties of concrete with RA after particle shaping [170–172].

[178] found that the presoak treatment of PVA polymer solution and sodium silicate solution can improve the properties of RA and prepared RAC due to that the presoak treatment increased the dense of RA. Furthermore, the waterproofing treatment of silane gel can well reduce the water absorption of RA and improve the water permeability resistance of RAC [179].

The carbonation is frequently harmful to the concrete durability, which reduces the basicity and results in the steel corrosion of reinforce concrete, whereas the microstructure, strengths, and dense of concrete after carbonation are generally improved [180–182]. Basing on the positive effect of carbonation reaction, Shi et al. [183] proposed that the carbonation treatment was used to modify the properties of RA and RAC. Figure 14 gives the SEM images of adhered old mortar and ITZ of RA with and without carbonation treatment. The results highlight that more pores and ettringite with a large size can be observed on the adhered mortar and ITZ of RA without carbonation treatment. In contrast, for the RA after carbonation treatment, the pores and ITZ can be well filled by the carbonation products, which improves the pore structure of RA, as shown in Figure 14(b). Thus, the carbonation treatment improves the properties of RA.

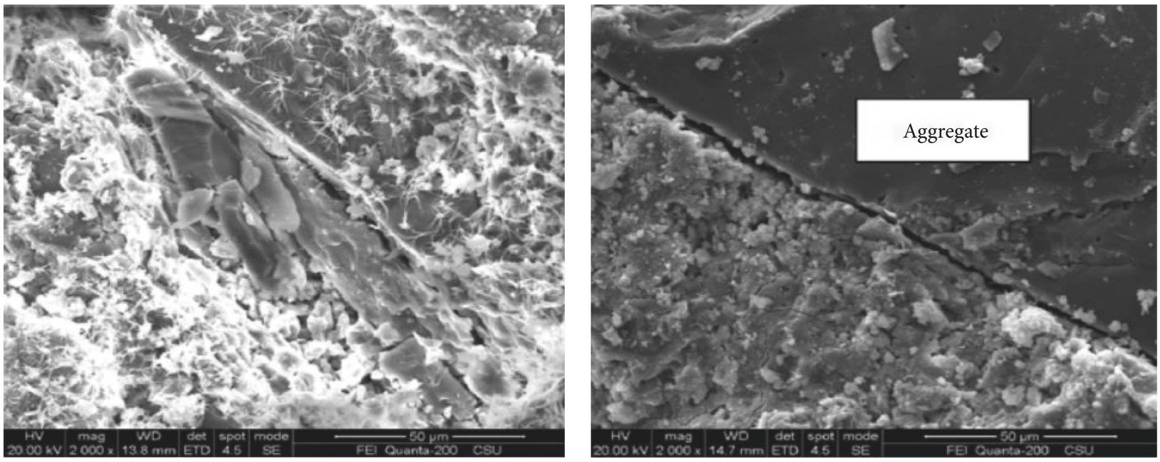
Figure 15(a) gives the characteristics of RA after carbonation. Although the properties of RA are still lower than that of NA, the properties of RA after carbonation are better than that without carbonation. For example, the water absorption of RA with and without carbonation treatment is, respectively, 2.42 and 3.31 times as high as that of NA, and the results become 1.46 and 1.58 times for the crushing index. Furthermore, the durability of concrete with and without carbonated RA was determined by Wang [184]. As shown in Figure 15(b), the durability of concrete with carbonated RA is better than that with noncarbonated RA; however, the durability of concrete with carbonated RA is still lower than that with NA. For example, the chloride diffusion coefficient of concrete with noncarbonated and carbonated RA is, respectively, 1.61 and 1.06 times as large as that of NAC, and the results are 1.31 and 1.17 for the carbonation depth.

4.3. Other Improvement Methods. The grading of RA has an obvious impact on the durability properties of RAC [185]. Xiao et al. [186] proposed that the properties of RAC can be improved by optimizing and adjusting the grading of RA, and Chen [112] further found that the RAC after grading adjustment had a better carbonation resistance than that without grading adjustment. This is due to that the grading adjustment of RA can make the prepared concrete denser, and the mechanical properties and durability performance are improved.

By the results of SEM, the water film is easy to form around the RA when it is first mixed with the free water in the process of mixture mixing, which is harmful to the ITZ properties of RAC. Comparing with various methods of RAC mixing, Wang [187] proposed a new preparation method of RAC, and the free water was divided into three parts and the mixing process was divided into four steps, which was named as the "W3T4" and is described in Figure 16. He found that the new mixing method can reduce the porosity of RAC, and more hydration products (such as C-S-H) were produced to fill the pores and cracks in the adhered old mortar and ITZ of RA. Comparing with the traditional mixing method of RAC, the mixing methods of "W3T4" significantly reduced the chloride permeability of RAC.

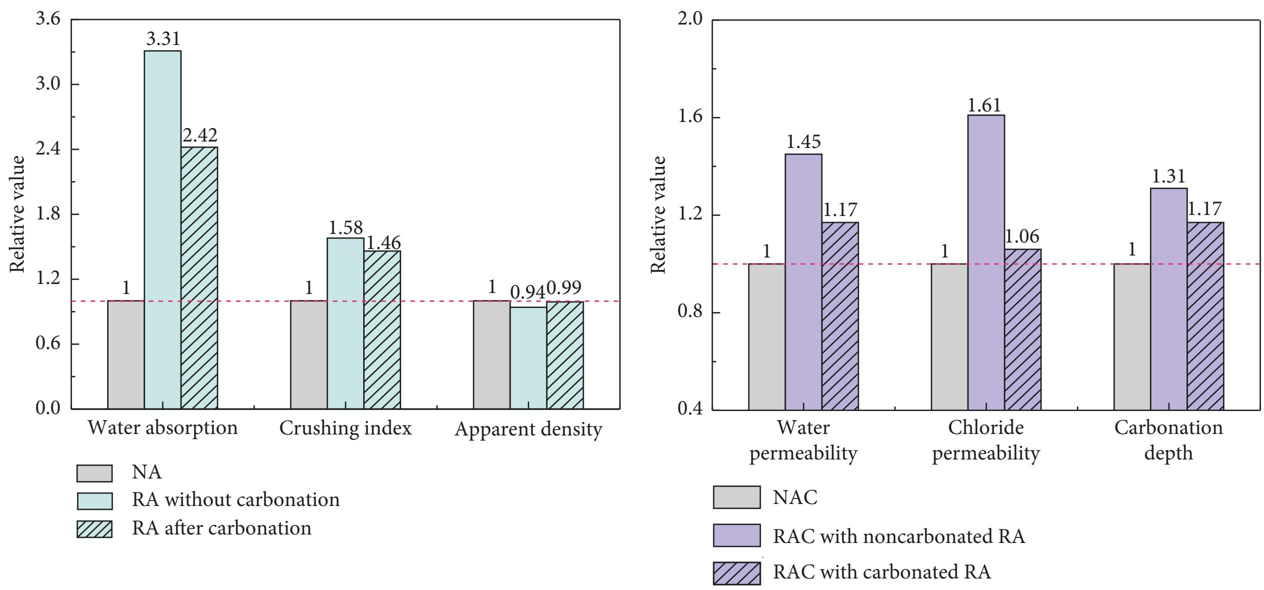
Some attempts are also developed to improve the durability of RAC by modifying the new mortar of RAC, and these modification methods are also suitable for the ordinary concrete. Jiang et al. [188] and Chen et al. [189] presented that the addition of mineral admixtures can improve the durability of RAC. The addition of waste rubber powder increased the freeze-thaw resistance of RAC [190]. Furthermore, Wang et al. [191], Fan et al. [192], and Zhang et al. [193] investigated the effects of nanomaterials on the durability of RAC, and the results showed that the addition of nanomaterials reduced the porosity and improved the durability properties of RAC, which was attributed to that the nanomaterials had a good filling effect and pozzolanic effect. Referring to the measurement technique of NAC, new visualization technology can also be used to evaluate the durability of RAC [194, 195].

Although many studies on the durability of RAC have been conducted and obtained some valuable conclusions in China over the past decade, there still exist some shortcomings which should be studied in the further studies. For example, the alkali-silica reaction of concrete with various types and quality of RA should be investigated, and it is the key indicator of the durability of concrete with recycled glass aggregate. Considering RAC is inevitably subjected to the harsh environment, the durability of RAC with the coupling effects of environmental damage should also be investigated in the future.



(a) (b)

Figure 14: SEM images of old mortar and ITZ of RA with and without carbonation [183]. (a) RA and (b) RA after carbonation.



(a) (b)

Figure 15: Durability properties of concrete with RA after carbonation modification [184]. (a) Characteristics of RA after carbonation and (b) durability properties of RAC.

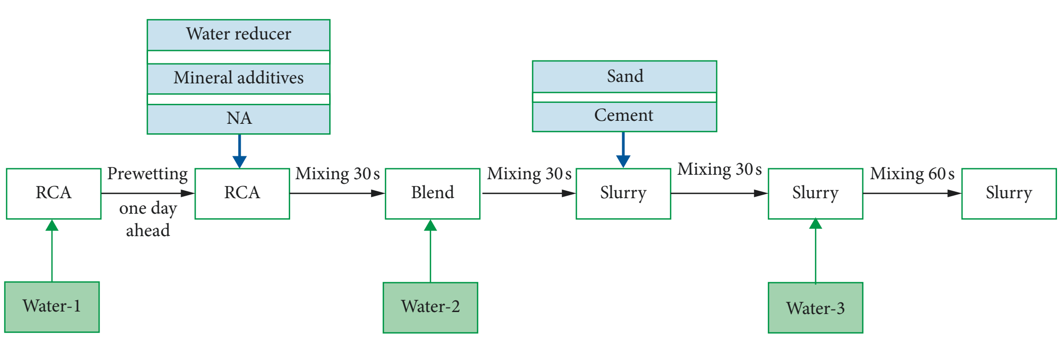


Figure 16: Preparing high-durability RAC by the mixing method of “W3T4” [187].

5. Conclusions

This study reviews the related studies on the durability of RAC in China over the past decade, and the effects of RA quality and replacement percentages are also considered. Furthermore, the improving methods of RAC durability are introduced. Based on the review of related literatures and discussions, the following conclusions can be drawn:

(1) Distinguishing with the C&D wastes in other countries and regions, the C&D wastes in China contain a complex composition. The waste concrete, waste bricks, and waste ceramics account for about 80% of the whole C&D wastes by weight. The recycled concrete aggregates, recycled brick aggregates, and recycled ceramics aggregates are the main types of RA in China, and the recycled brick aggregates and the recycled ceramic aggregates, respectively, have the highest and the lowest water absorption. Particularly, this paper proposes an index of average water absorption rate to comprehensive evaluate the properties of RA, which simultaneously considers the effects of the replacement percentages and quality of RA.

(2) The addition of RA plays negative effects on the durability of RAC. By data fitting, the durability properties generally decrease linearly with the increase of RA replacement percentages and the average water absorption rate. The fitting data discreteness of average water absorption rate is generally lower than that of RA replacement percentages, which manifests the average water absorption rate is an appropriate index to quantify the durability of RAC. When the RA replacement percentages are the same, the durability properties reduce with the increase of RA average water absorption rate, which manifest that the inferior properties of RA aggravate the durability degeneration of RAC.

(3) Removing and enhancing the adhered old mortar of RA are two main methods to improve the RA properties and RAC durability. Above 90% of adhered old mortar can be removed by the treatment of particle shaping, and the quality of RA after particle shaping can be closed to that of NA, and the durability properties of RAC with shaping RA are improved. The carbonation treatment is also an effective method to improve the properties of RA and prepared RAC, and it is more sustainable for the construction industry because the carbonation reaction absorbs CO_2 gas. Furthermore, optimizing the mixing method of RAC mixture, adjusting the RA grading, and adding nanomaterials can also improve the durability of RAC.

Data Availability

The data in this manuscript were obtained through review of the published literature studies. The related data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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