Review Article

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An overview of bond behavior of recycled coarse aggregate concrete with steel bar

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Abstract: In this paper, an overview focusing on the bond behavior of recycled coarse aggregate concrete (RAC) with steel bar is carried out. The results show that the failure modes of RAC specimen were not only influenced by a single factor, it is necessary to comprehensively consider the influence of various factors on the failure modes of RAC specimen; The steel bar diameter, the concrete cover to diameter ratio and the replacement rate of RCA all affect the load-slip curve of RAC specimen; Bond strength predictive equations and bond-slip relationship models of RAC with steel bar has been summarized to ensure engineers to better understand their applicability; The influencing factors of the bond behavior of RAC specimens including the replacement rate of RCA, the concrete compressive strength, the steel bar type and steel bar diameter, the steel bar embedment length and the aggregate performance; The freeze-thaw cycles and the steel bar corrosion all affect the bond behavior of RAC with steel bar. When freeze-thaw damage and steel bars corrosion reach a certain degree, the bond behavior of RAC with steel bar deteriorates.

Keywords: recycled coarse aggregate concrete, bond strength, prediction model, freeze-thaw cycles, steel bar corrosion

1 Introduction

In recent years, the problem of environmental pollution has attracted more and more attention [1]. A large amount of construction and demolition waste (CDW) will be produced during the demolition of the old building, of which the demolished concrete waste accounts for a large proportion, and it will cause serious environmental pollution [2]. In addition, the new buildings will consume a lot of natural resources. The recycling and reusing of the CDW has become a focus of research work in recent years.

Scholars also try to apply new technologies to concrete [3]. Recycling CDW through the development and application of RAC is a new way [4]. The RAC refers to a new type of concrete that uses coarse aggregates and fine aggregates extracted from CDW instead of natural aggregates [5, 6]. The technology of RAC can solve the problem of environmental pollution caused by CDW [7, 8]. At the same time, it can reduce the consumption of natural aggregates [9]. Therefore, the technology of RAC is beneficial from the perspective of resources saving and environment protection [10]. More and more scholars began to investigate RAC [11].

The bond behavior between concrete and steel bar is a key factor to ensure the two materials work together. Unlike NCA, RCA has more porous and higher water absorption, which is because the old cement paste on its surface will influence the bond behavior between concrete and steel bar [12–15]. Some studies on the bond behavior between RAC and steel bar have been conducted through beam-type test or pull-out test. It can be seen that many factors could influence the bond behavior between RAC and steel bar, such as replacement rate of RCA, concrete compressive strength, steel bar diameter, steel bar embedment length, etc [16–18]. In addition, the bond strength prediction equations and the bond-slip prediction models of RAC and with bar were proposed by considering different influencing factors [16]. However, there was no universal bond strength prediction equations and bond-slip prediction models between RAC and steel bar. Therefore, it was necessary to summarize the existing bond strength prediction equations and bond-slip relationship prediction models between RAC

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and steel bar to ensure engineers to better understand their applicability.

Moreover, laboratory tests also revealed that the harsh environments (such as freeze-thaw cycles and steel bar corrosion) could accelerate the degradation of bond behavior of RAC with steel bar, which made the research more complicated [19]. Therefore, it was necessary to further research on the bond behavior of RAC with steel bar for the application of RAC in reinforced concrete (RC) structures.

In this paper, the failure modes, the bond-slip curves, the bond strength prediction equations, the bond-slip relationship prediction models and the critical influencing factors of the bond behavior of RAC with steel bar were reviewed. Furthermore, the bond behavior of RAC specimens after freeze-thaw cycles and steel bar corrosion were presented, respectively.

2 Failure modes and bond-slip curves of RAC with steel bar

2.1 Failure modes

The failure modes of RAC with steel bar are shown in Figure 1, it can be seen that the failure modes of RAC spec-

imens were similar to that of NAC specimens. The main failure modes of RAC with steel bar are as follows:

- 1) Pullout failure. The relative slip occurred between the RAC and steel bar, and the steel bar was slowly pulled out from RAC. There was no crack on the surface of RAC specimen, which was shear failure.
- 2) Splitting failure. The RAC specimens were suddenly split into two or three parts, which was brittle failure.
- 3) Pullout-splitting (P-S) failure. The splitting cracks occurred on the surface of RAC specimen when the steel bar was pulled out from RAC.
- 4) Rebar yielding (RY) failure. The steel bar occurred yielding failure during the loading process.

The author compared the bond failure modes of NAC specimens and RAC specimens through pullout test [19], and the results are shown in Figure 2. The bond failure modes of RAC specimens and NAC specimens were the pullout-splitting failure, but the cracks of NAC specimens were larger than those of RAC specimens, the reason is that the fracture energy of NAC is greater than that of RAC.

Figure 1: Failure modes of RAC specimens: (a) Pullout failure; (b) Splitting failure; (c) Pullout-splitting failure; (d) Rebar yielding failure.

Figure 2: Failure modes of NAC and RAC specimens.

Table 1: Factors for determining the failure modes

w/c	Concrete strength (MPa)	Replacement rate of RCA (%)	Steel bar diameter (mm)	Steel bar type	Cover depth (mm)	Stirrups	Embedment length (mm)	Failure modes
0.51	29.26	0	16	Deformed	67	-	64	Pullout
	26.52	30						Pullout
	28.53	60						Pullout
	27.08	100						Pullout
Kim <i>et al.</i> [18]	33.42	0	16	Deformed	67	-	64	P-S
	31.46	30						P-S
	30.66	60						P-S
	29.49	100						Pullout
0.33	44.13	0	16	Deformed	67	-	64	Splitting
	39.50	30						Splitting
	43.80	60						Splitting
	42.44	100						Splitting
Guerra <i>et al.</i> [20]	48.5	0	12	Deformed	94	-	5d/10d/15d	Splitting
	49.3	20						Splitting
	47.9	50						Splitting
	43.4	100						Splitting
0.52	48.5	0	16	Deformed	92	-	5d/10d/15d	Splitting
	49.3	20						Splitting
	47.9	50						Splitting
	43.4	100						Splitting
0.43	43.1	0	14	Deformed	68	-	75	P-S
								Splitting
								Splitting
0.43	41.2	50	14	Deformed	68	-	75	Splitting
								Splitting
								Splitting
0.43	45.2	100	14	Deformed	68	-	75	Splitting
								Splitting
								Splitting
Jun [23]	45.2	100	16	Deformed	67	-	75	Splitting
	45.2							Splitting
	42.8							Splitting
							75	Splitting

0.43	42.8	100	20	Deformed	65	-	100	Splitting Splitting
							125	
0.43	42.8	100	20	Plain	65	-	75	Pullout
							100	Pullout
							125	Pullout
Zhao and Wang [24]	0.51	0/30/50/100 0/30/50/100	20 20	Deformed Plain	75	-	3d/5d/7d	Splitting Pullout
							5d/8d/10d	Splitting
	0.40	30	16	Deformed	67	-	12d	RY
						✓	5d/8d	Pullout
						✓	10d/12d	RY
Ren [26]						-	5d/8d/10d	Splitting
	0.35	40	16	Deformed	67	-	12d	RY
						✓	5d/8d	Pullout
						✓	10d/12d	RY
	0.32	50	16	Deformed	67	-	5d/8d	Splitting
						-	10d/12d	RY
						✓	5d/8d	Pullout
						✓	10d/12d	RY
Butler et al. [28]	0.60	30	25.2	Deformed	30	✓	125	P-S
	0.38	50					375	P-S
	0.50	55.2	18	Deformed	91	-	180	P-S
							360/450	RY
Wang et al. [29]	0.50	49.2	18	Deformed	91	-	180	P-S
							360/450	RY
	0.50	44.6	18	Deformed	91	-	180	P-S
							360/450	RY
	0.67	25-30	0	Deformed	50/49	-	5d	Pullout
	0.68	25-30	100					Pullout
	0.67	25-30	0	Deformed	50/49	-	10d	RY
	0.68	25-30	100					RY
Wardeh et al. [30]	0.59	35-40	0	Deformed	50/49	-	5d	Pullout
	0.55	35-40	100					Pullout
	0.59	35-40	0	Deformed	50/49	-	10d	RY
	0.55	35-40	100					RY

Several investigations have been performed on the influence of various factors on the failure modes of RAC with steel bar. Table 1 shows the results of Literature [18, 20, 23, 24, 26, 28–30]. The test results of Kim *et al.* [18] showed that the water-to-cement ratio (w/c) was the critical influencing factor on the failure mode of RAC specimens, the failure mode was pullout failure when the water-to-cement ratio was 0.51; the failure mode was pullout-splitting failure when the water-to-cement ratio was 0.46; the failure mode was splitting failure when the water-to-cement ratio was 0.33. The reason is that the fracture energy of higher strength concrete is greater than that of lower strength concrete. A noticeable point is that when the replacement rate of RCA was 100%, the failure modes of the specimens with 0.46 water-to-cement ratio was pullout failure. Therefore, it can be speculated that the replacement rate of RCA was another factor affecting the failure mode of RAC specimens. The test results of Guerra *et al.* [20] showed that the steel bar diameter was the critical influencing factor on the failure mode of RAC specimen. Guerra *et al.* [20] point out that the RAC specimens with smaller steel bar diameter (12 mm) exhibited more radial cracks and lower crack widths, while the RAC specimens with larger steel bar diameter (12 mm) exhibited fewer radial cracks and wider crack widths. Jun [23] investigated the influence of the steel bar type, the steel bar diameter, the replacement rate of RCA, the concrete cover depth and the embedment length on the failure mode of RAC specimens, and found that the steel bar type was the critical influencing factor on the failure mode of RAC specimen, the failure mode of RAC specimens with deformed steel bar was splitting failure or pullout-splitting failure, while that of RAC specimens with plain steel bar was pullout failure. This agrees with the findings of Zhao and Wang [24] and Li *et al.* [25]. The test results of Ren [26] showed that the concrete strength, the embedment length and the stirrup could affect the failure mode of RAC specimen, and the stirrup was the critical influencing factor. The result was similar to that reported by Xu *et al.* [27]. Butler *et al.* [28] discovered that when the concrete cover depth was small, the splitting cracks occurred on the surface of RAC specimen when the steel bar was pulled out regardless of concrete compressive strength or embedment length. The test results of Wang *et al.* [29] showed that the embedment length is the critical influencing factor on the failure mode of RAC specimen, the failure mode of RAC with larger embedment length was rebar yielding failure, while that with smaller embedment length was splitting failure. The test results of Wardeh *et al.* [30] discovered a similar conclusion that the failure mode of RAC specimens with smaller embedment length (equal to 5 times the steel bar diameter) was pullout failure regardless of the steel bar diameter,

the concrete strength and the cover depth, while that with larger embedment length (equal to 10 times the steel bar diameter) was rebar yielding failure.

Actually, the failure modes of RAC specimen were not only influenced by a single factor [31]. Therefore, it is necessary to comprehensively consider the influence of various factors on the failure modes of RAC specimen, such as the water-to-cement ratio, the concrete strength, replacement rate of RCA, the steel bar diameter, the steel bar type, the concrete cover depth, the stirrups, the embedment length. In addition, the water-to-cement ratio and the concrete strength can be regarded as the same influencing factor; Because the steel bar diameter can affect the concrete cover depth, the ratio between the concrete cover depth and the steel bar diameter (c/d) can be used as an influencing factor.

2.2 Bond-slip curves

Previous research has shown that the development and deterioration of bond behavior of RAC specimens was fundamentally similar to that of NAC specimens, and there was no noticeable difference in the load-slip curves between RAC and NAC specimens [42–46].

Generally, the load-slip curves of RAC specimens with pullout failure or pullout-splitting failure include the micro-slip branch, the internal cracking branch, the pullout branch, the descending branch and the residual branch. In the micro-slip branch, the load-slip curve was almost linear, the load was small and the slip at the steel bar free end was not obvious; In the internal cracking branch, the slip at the steel bar free end began to appear. In this branch, the adhesion force had nearly been exhausted; In the pullout branch, the slip increased rapidly, the load-slip curve became non-linear, and then the pullout load reached the peak value. In this branch, the splitting cracks occurred in the concrete cover in some cases; In the descending branch, the pullout load decreased rapidly and the slip increased rapidly; In the residual branch, the pullout load was almost constant when the slip increased to a certain value. However, the bond-slip curves of RAC specimens with splitting failure or rebar yielding failure was incomplete with only ascending branch.

However, Kim and Yun [36] reported that the ascending branch of the load-slip curve of RAC specimens was more non-linear than that of NAC specimens. The result was similar to that reported by Xiao and Falkner [34]. Several investigations have been performed on the influence of various factors on the load-slip curves of RAC with steel bar. Prince [32, 33, 35] point out that the ascending branch of the load-slip curves of RAC with larger steel bar diameter

almost linear up to peak load, the internal cracking branch and the pullout branch were indistinguishable. Pour and Alam [37] reported that the pullout branch became distinguishable when the concrete cover to diameter ratio was larger, and the slope of the descending branch was relatively small, which was due to the higher toughness. Li *et al.* [25] investigated the influence of the replacement rate of RCA on the load-slip curves of RAC, and found that there was not obvious relationship between the slope of the ascending and descending branch and the replacement rate of RCA.

3 Bond strength predictive equations and bond-slip relationship models

Currently, several bond strength predictive equations and bond-slip relationship models of RAC with steel bar have been established according to experimental data, as described in the following sections.

3.1 Bond strength predictive equations

Kim *et al.* [18] proposed a multivariable model as shown in Equation (3) taking into account the average density of the coarse aggregates and the concrete compressive strength.

$$r = 1.039 \times \left[0.925 \times \frac{\rho_{AVE}}{\rho_{NCA}} \right]^{\left[\frac{4}{(0.04F_c)^2} \right]} \quad (1)$$

$$r = \frac{\tau_{RAC}}{\tau_{NAC}}$$

$$F_c = \begin{cases} 30, & f_c \leq 30 \\ f_c, & \text{other case} \end{cases}$$

Where ρ_{AVE} is the average density of the coarse aggregates; ρ_{NCA} is the density of the NCA; f_c is the concrete compressive

strength; τ_{RAC} is the bond strength of RAC specimens; τ_{NAC} is the bond strength of NAC specimens.

Wardeh *et al.* [30] proposed a new model taking into account the concrete compressive strength, the steel bar diameter, the concrete cover, the embedded length and the replacement rate of RCA:

$$\tau_{\max} = \frac{\left[-0.33 + 0.4 \left(\frac{c}{d} \right) + 9.5 \left(\frac{l_d}{d} \right) \right]}{1 + 0.125\gamma} \sqrt{f_{cm}} \quad (2)$$

Where γ is the replacement rate of RCA; l_d is the embedded length; d is the steel bar diameter; f_{cm} is the cylinder compressive strength;

Seara-Paz *et al.* [38] proposed a modified expression based on the prediction equation in Model Code-2010 [39]:

$$\tau_{\max} = 2.5 \sqrt{f_{cm}} (1 - 0.124\gamma/100) \quad (3)$$

Kim *et al.* [40] proposed a predictive equation taking into account the concrete compressive strength, the replacement rate of RAC and recycled fine aggregates (RFA), the steel bar diameter and the concrete cover depth.

$$\tau_{\max} = 0.614 \sqrt{f_{ckr}} (c/d - 0.55) - \left(0.4203e^{0.0172S} + 0.007\gamma \right) \quad (4)$$

Where f_{ckr} is the mean value of cylinder compressive strength; c is the concrete cover depth; S is the replacement rate of RFA.

A comparison among these bond strength predictive equations is summarized and listed in Table 2, to better understand the factors that affect bond strength considered in the predictive equations, and their applicability.

It is clear that the concrete compressive strength is taken into account for all these predictive equations. Average density of coarse aggregates is considered only in the bond strength predictive equations of Kim *et al.* [18]; Replacement rate of RFA is considered only in the bond strength predictive equations of Kim *et al.* [40]; Embedment length is considered only in the bond strength predictive

Table 2: Factors for determining bond strength predictive equations

Predictive equations	Average density of coarse aggregates	Concrete compressive strength	Steel bar diameter	Replacement rate of RCA	Cover depth	Replacement rate of RFA	Embedment length
Kim <i>et al.</i> [18]	✓	✓	×	×	×	×	×
Wardeh <i>et al.</i> [30]	×	✓	✓	✓	✓	×	✓
Seara-Paz <i>et al.</i> [38]	×	✓	×	✓	×	×	×
Kim <i>et al.</i> [40]	×	✓	✓	✓	✓	✓	×

equations of Wardeh *et al.* [30]. Replacement rate of RCA is a critical influencing factor of bond strength, but which is ignored in the bond strength predictive equations of Kim *et al.* [18]; Steel bar diameter and concrete cover depth are ignored in the bond strength predictive equations of Kim *et al.* [18] and Seara-Paz *et al.* [38]. It is worth noting that the stirrup is not considered in those bond strength predictive equations, and it is necessary to be further investigated.

Comparison between predicted data determined using Eq. (1-4) and experimental values of [19] is shown in Figure 3. The difference between the experimental value and the predicted value determined using Eq. (1-3) was not great, while the predictive equation of Kim *et al.* [40] greatly underestimated the bond strength of RAC specimens. The reason is that the predictive equation of Kim *et al.* [40] is suitable for RAC specimens containing RCA and RFA, while the specimens of [19] do not contain RFA.

Figure 3: Comparison between predicted values and experimental values of bond strength.

3.2 Bond-slip relationship models

3.2.1 Xiao's model

Xiao [34, 41] proposed a normalized bond-slip relationship model of RAC with steel bar, which was obtained by modifying the equations proposed by Harajli [42] and Guo [43].

$$\bar{\tau} = \begin{cases} (\bar{s})^a, & \bar{s} \leq 1 \\ \frac{\bar{s}}{b(\bar{s}-1)^2 + \bar{s}}, & \bar{s} > 1 \end{cases} \quad (5)$$

$$\bar{\tau} = \frac{\tau}{\tau_{\max}} \quad (6)$$

$$\bar{s} = \frac{s}{s_{\max}} \quad (7)$$

Where $\tau_{\max}$ is the ultimate bond strength; $s_{\max}$ is the slip page corresponding to the ultimate bond strength; a and b are constants which determined base on the experimental results.

Many scholars established the corresponding bond-slip models based on the model proposed by Xiao and Falkner [34] and Xiao *et al.* [41] by considering the influence of various factors on the parameter a and b . Li *et al.* [25] found that the parameter a of RAC with plain steel bar was 0.15, while that with deformed steel bar was 0.1. Wardeh *et al.* [30] investigated the influence of the steel bar diameter on the values of parameter b , and found that the values of parameter b decreased with the increase of steel bar diameter. Xiao and Falkner [34] point out that the parameter a was determined to 0.3, whatever the replacement rate of RCA or mix proportion, and the values of parameter b of RAC with deformed steel bar were much higher than that with plain steel bar. Prince and Singh [32] investigated the bond-slip model of high strength RAC with steel bar, and found that the values of parameter a and b were 0.18 and 0.20 respectively when the steel bar diameter was 8 mm, while the values of parameter a and b were 0.20 and 0.15 respectively when the steel bar diameter was 10 mm. Prince and Singh [33] studied the bond-slip model of RAC with different steel bar diameter, the results showed that the values of parameter a were in a narrow range, regardless of the replacement rate of RCA. This agrees with the findings of Kim *et al.* [44]. Prince and Singh [33] also pointed out that there was no obvious relationship between the values of parameter b and the replacement rate of RCA. However, Xiu [45] revealed different conclusion that the parameter b decreased with the increase of replacement rate of RCA, and it increased with the increase of concrete compressive strength. Prince and Singh [49] reported that the values of parameter b of RAC with 10 mm steel bar increased with the increase of the replacement rate of RCA, while this trend was not clearly when the steel bar diameter was 8 mm.

According to the bond-slip relationship model, the smaller the value of parameter a , the steeper the ascending branch of the curve; and the smaller the value of parameter b , the smoother the descending branch of the curve. A comparison among these bond strength predictive equations is summarized and listed in Table 3. It was clear that key factors such as, the steel bar type, the concrete compressive strength, the steel bar diameter and the replacement rate of RCA have been considered in previous studies. Actually, the factors affecting the bond-slip curve will also affect the values of parameter a and b . However, the concrete cover depth, embedded length and the stirrup are ignored, and it is necessary to be further investigated.

Table 3: Factors for determining parameter a and b

Predictive equations	Parameter	Steel bar type	Concrete compressive strength	Steel bar diameter	Replacement rate of RCA
Kim <i>et al.</i> [18]	a	✓	-	-	-
	b	✓	-	-	-
Wardeh <i>et al.</i> [30]	a	-	-	-	-
	b	-	-	✓	-
Prince and Singh [32]	a	-	-	✓	-
	b	-	-	✓	-
Prince and Singh [33]	a	-	-	-	✓
	b	-	-	-	✓
Xiao and Falkner [34]	a	-	-	-	-
	b	✓	-	-	-
Xiu [45]	a	-	-	-	-
	b	-	✓	-	✓
Prince and Singh [49]	a	-	-	-	-
	b	-	-	✓	✓

3.2.2 Prince's model

Prince and Singh [35] proposed a new bond-slip relationship model between RAC and steel bar with only parameter a , which based on the model proposed by Xiao [34] and Xiao *et al.* [41]:

$$\bar{\tau} = \begin{cases} (\bar{s})^a, & \bar{s} \leq 1 \\ \left(\frac{1}{\bar{s}}\right) + 0.15\tau_{\max}, & \bar{s} \geq 1 \end{cases} \quad (8)$$

Prince and Singh [35] reported that the value of parameter a was about 0.2 for the normal-strength (36 MPa) and high-strength (68 MPa) RAC specimens, while it was about 0.3 for the medium-strength concrete (51 MPa).

3.2.3 Three-stage model

Cao *et al.* [50] proposed a three-stage relationship model between RAC and steel bar:

$$\tau = \begin{cases} \tau_{\max} \left(\frac{s}{s_{\max}}\right)^a, & 0 \leq s \leq s_{\max} \\ \tau_{\max} - \left(\frac{\tau_{\max} - \tau_c}{s_1 - s_{\max}}\right)(s - s_{\max}), & s_{\max} \leq s \leq s_1 \\ \tau_c, & s > s_1 \end{cases} \quad (9)$$

Where τ_c is the residual bond strength; s_1 is the slippage corresponding to the residual bond strength; a is parameter that can be determined base on the experimental results.

Wang [19] proposed another three-stage relationship model between RAC and steel bar:

$$\tau = \begin{cases} \left[(0.8 + 0.16a^{-1})\frac{s}{s_{\max}}\right] \tau_{\max}, & 0 \leq \frac{\tau}{\tau_{\max}} \leq 0.8 \\ -a\frac{s}{s_{\max}} + a + 1 \tau_{\max}, & 0.8 \leq \frac{\tau}{\tau_{\max}} \leq 1 \\ -b\frac{s}{s_{\max}} + b + 1 \tau_{\max}, & \frac{s}{s_{\max}} \geq 1 \end{cases} \quad (10)$$

Where a and b are parameters that can be determined base on the experimental results.

The bond-slip relationship model proposed by Prince and Singh [35] and the three-stage relationship model were not widely applied. Although the bond-slip relationship model proposed by Xiao [34] and Xiao *et al.* [41] was widely applied, there was still no uniform regulation for the selection of the values of parameter a and b , and the influence of some factors, such as the concrete cover depth, the embedded length and the stirrup on parameter a and b has not been investigated, and it is necessary to be further investigated.

4 Critical influencing factors on the bond behavior

In this section, more than 30 existing literature were collected to investigate the influencing factors of the bond behavior of RAC with steel bar. This section indicated that the critical influencing factors (including the replacement rate of RCA, the concrete compressive strength, the steel bar type, the steel bar diameter, the steel bar embedment

length and the aggregate performance) and other influencing factors on the bond behavior of RAC with steel bar, and a detailed discussion is given below.

4.1 Replacement rate of RCA

Several investigations have been performed on the influence of the replacement rate of RCA on the bond behavior of RAC with steel bar, and there were still opposite opinions in existing research. Several previous studies point out that the bond strength increased with the increase of replacement rate of RCA [20, 29, 46–48].

It is widely accepted that the bond behavior of concrete will also increase with the improvement of mechanical properties. Therefore, it was necessary to take into account the influence of the compressive strength of RAC when analyzing the influence of RCA on the bond strength [38]. Most studies defined the normalized bond strength $\tau/\sqrt{f_c}$ (τ is the bond strength, and f_c is the concrete compressive strength) to eliminate the influence of concrete strength. Prince and Singh [32, 33, 49] point out that the replacement rate of RCA had no detrimental influence on the normalized bond strength $\tau/\sqrt{f_c}$ of RAC with steel bar. On the contrary, it had a tendency to increase as the replacement rate of RCA increase. This agrees with the findings of Kim and Yun [36], Li *et al.* [25] and Xiao and Falkner [34]. Li *et al.* [25] tended to indicate the reason is that the surface of RCA is rougher and the biting force between RCA and new cement paste is greater. Xiao and Falkner [34] revealed the reason is that the elasticity modulus of RCA is similar to that of the cement paste, which improves the composite action between RCA and the cement paste.

For direct comparison, selected the results (the normalized bond strength) from the literature [25, 32–34, 36, 49], are plotted in Figure 4 which shows that the normalized bond strength increased with the increase of replacement rate of RCA.

In addition, Prince and Singh [35] point out that the traditional normalized bond strength ($\tau/\sqrt{f_c}$) overestimated the influence of concrete strength, resulting in the bond strength of high-strength concrete was overestimated. Therefore, the paper redefined a new normalized bond strength $\tau/\sqrt[3]{f_c^4}$. The normalized bond strength ($\tau/\sqrt[3]{f_c^4}$) of RAC increased with the increase of replacement rate of RCA. The reason is that the brittleness index (the ratio of compressive strength to the splitting tensile strength) decreases with the increases of replacement rate of RCA, resulting in a higher fracture toughness of RCA.

However, some other test results showed that the bond strength decreased with the increase of replacement rate

Figure 4: Normalized bond strength versus replacement rate of RCA (a).

of RCA. Guerra *et al.* [20] investigated the influence of the replacement rate of RCA on the pull-out force, and found that the pull-out force of RAC specimens was lower than that of NAC, when the replacement rate of RCA was higher than 50%. Butler *et al.* [28] conducted a beam-type experiment on the bond behavior of RAC with steel bar, and the results showed that the bond strength of RAC was lower than that of NAC. Pour and Alam [37] demonstrated that the normalized bond strength $\tau/\sqrt{f_c}$ of RAC with steel bar decreased with the increase of replacement rate of RCA, but this trend was not obvious. Kim *et al.* [44] reported that the ultimate bond strength decreased with the increase of the replacement rate of RCA, while the slippage corresponding to the ultimate bond strength increased. Kim *et al.* [18] and Seara-Paz *et al.* [38] had shown similar conclusion. Kim *et al.* [18] also point out that the reason is that the density of RCA is lower than that of NCA, while the water absorption of RCA is higher.

For direct comparison, selected the results (normalized bond strength) from the literature [18, 37, 38, 44] was calculated and plotted in Figure 5, which shows that the normalized bond strength decreased with the increase of replacement rate of RCA.

In addition, Kim *et al.* [31] reported that with the increase of replacement rate of RCA, the difference between bond strength and slippage corresponding to the ultimate bond strength of high strength concrete were not significant. Fernandez *et al.* [52] point out that the bond strength of the RAC specimen was comparable to that of NAC specimen. Breccolotti and Materazzi [53] revealed that the normalized bond strength of RAC was only slightly affected by the replacement level of RCA. Qiong *et al.* [54] demonstrated that the bond strength of RAC increased first and then de-

Figure 5: Normalized bond strength versus replacement rate of RCA (b).

creased with the increased of the replacement rate of RCA, but it was always higher than that of NAC. The reason is that the RCA still absorbs the free water during the curing process, which reduces the influence of water-cement ratio. When the replacement rate of RCA is high, the strength increase caused by the reduction of the influence of water-cement ratio becomes the secondary influencing factors, and the strength decrease caused by various unfavorable factors (such as higher discreteness, higher mud content and higher crushing index) becomes the critical influencing factors [55].

It can be seen that there were still opposite opinions about the influence of replacement rate of RCA on the bond strength in existing research, the reason is that most scholars only obtain the mix proportions of concrete with different replacement rate of RCA by replacing NCA with RCA, and maintained the same water-cement ratios, without considering the influence of different replacement rates of RCA on the concrete compressive strength. Butler *et al.* [28] investigated the bond behavior between RAC with two types of concrete mixture proportions and steel bar. The first type maintained the same water-cement ratios, while the second type was designed to obtain the same concrete compressive strengths. The results showed that the bond strength of NAC specimens was 10.4 to 19% higher than the first type RAC specimens, and 9.4 to 21.3% higher than the second type RAC specimens. It can be seen that it was necessary to take into account the influence of different replacement rates of RCA on the concrete compressive strength when analyzing the influence of RCA on the bond strength. Although the normalized bond strength ($\tau/\sqrt{f_c}$ and $\tau/\sqrt[3]{f_c^4}$) was used to eliminate the influence of concrete compressive strength on bond strength, the best way was to adjust the mix proportions of concrete to ensure that the concrete

with different replacement rate of RCA. The bond strength of RAC with has same concrete compressive strength. This method can be widely used in future research.

4.2 Concrete compressive strength

Concrete compressive strength was another critical factor that influence the bond behavior of RAC with steel bar. Jun [23] and Ren [26] investigated the influence of the concrete compressive strength on the bond strength of RAC specimens, the results showed that the bond strength of RAC specimens increased with the increase of concrete compressive strength, the reason is that the chemical adhesion and the mechanical bite force between RAC and steel bar increases with the increase of concrete compressive strength. Xiu [45] revealed the similar conclusion that the ultimate bond strength and the normalized bond strength of RAC specimens increased with the increase of compressive strength of RAC. Seara-Paz *et al.* [38] reported that the ultimate bond strength of RAC specimens with 0.5 water-cement ratio (relatively high concrete compressive strength) was higher than that with 0.65 water-cement ratio (relatively low concrete compressive strength). Prince and Singh [32] had shown similar conclusion that the normalized bond strength of high-strength RAC was higher than that of normal-strength RAC by comparison with Prince and Singh [49], which was in agreement with the findings of Esfahani and Rangan [56] for NAC specimens. Although Kim *et al.* [18] point out that the ultimate bond strength tended to decrease as the concrete compressive strength increased, the normalized bond strength (calculated in this paper) generally increased with the increase of concrete compressive strength.

In order to reduce the influence of mechanical properties on the bond strength, selected the results (normalized bond strength) from the literature [18, 23, 33, 38] was calculated and plotted in Figure 6 which shows that the normalized bond strength increased with the increase of compressive strength of RCA.

However, Prince and Singh [35] point out that the normalized bond strength ($\tau/\sqrt[3]{f_c^4}$) of normal-strength (36 MPa) RAC was higher than that of medium-strength (51 MPa) and high-strength (68 MPa) RAC.

Overall, in the aspect of the influence of concrete compressive strength on normalized bond strength of RAC specimens, it was widely accepted that the bond strength of RAC increased with the increase of concrete compressive strength. Prince and Singh [35] point out the reason is that brittleness index increases with the increase of concrete compressive strength, and the bond strength increases with

Figure 6: Normalized bond strength versus concrete compressive strength.

the increase of its brittleness index. The author thinks the reason is that the improvement of concrete strength improves the bonding effect on steel bars, and then improves the bond strength of RAC specimens.

4.3 Steel bar type and steel bar diameter

Similar to the replacement rate of RCA and the concrete compressive strength, the steel bar type and the steel bar diameter were other two critical factors that influence the bond strength of RAC with steel bar.

Jun [23], Li *et al.* [25], Xiao and Falkner [34] and Cao *et al.* [50] had investigated the influence of steel bar type on the bond behavior of RAC with steel bar, and found that the bond strength of RAC with deformed steel bar was much higher than that with plain steel bar. Xiao and Falkner [34] point out that the reason of this result is that the deformed

Figure 7: Bond strength versus steel bar type.

steel bars can provide stronger mechanical anchorage and friction resistance. Figure 7 shows the relationship between the bond strength of RAC specimens and the steel bar type.

It can be seen from Figure 7 that the bond strength of RAC with deformed steel bar was much greater than that with plain steel bars. Therefore, the steel bar type was a critical factor affecting the bond strength of RAC with steel bar. In order to ensure good bonding performance between steel bar and RAC, the deformed steel bar should be selected in RAC members.

In addition, Pour and Alam [37] found that the bond strength between RAC and steel bar decreased with the increase of steel bar diameter, and the bond strength of RAC with 19.5 mm was about 50% of that with 11 mm when the replacement rate of RCA was 30%. The reasons are following: On the one hand, the contact interface between RAC and steel bar increases with the increase of steel bar diameter, while the bond stress transferred to RAC decreases; On the other hand, the numbers of ribs under the same embedment length decreases with the increase of steel bar diameter. This agrees with the findings of Jun [23] and Cao *et al.* [50]. Prince and Singh [49] revealed the similar conclusion that the normalized bond strength of RAC with larger steel bar diameter was lower than that with smaller steel bar diameter. However, Li *et al.* [25] found that the bond strength increased with the increase of the steel rebar diameter.

The selected the results (normalized bond strength) from the literature [20, 25, 37, 49] was calculated and plotted in Figure 8 which shows that the normalized bond strength decreased with the increase of steel bar diameter except that of Li *et al.* [25].

Figure 8: Normalized bond strength versus steel bar diameter.

The bond strength of RAC with deformed steel bar is mainly the mechanical bite force between the steel bar ribs and RAC, while the main shape parameters of steel bars that affect the mechanical bite force are rib height and rib spacing. For the steel bar with same diameter, the higher the ribs, the smaller the spacing between ribs, the better the mechanical bite effect. The rib height and rib spacing of steel bars also change with the diameter of steel bars. Therefore, it is necessary to analyze the rib height and rib spacing as influencing factors when comparing the bond strength of RAC with different steel bar diameters.

4.4 Steel bar embedment length

A number of scholars conducted research regarding the influence of steel bar embedment length on the bond strength of RAC with steel bar [18, 23, 25, 26, 29, 30, 37, 50, 51, 54]. Pour and Alam [37] reported that the bond strength decreased with the increase of steel bar embedment length. The bond strength of RAC with $10d$ (d is the steel bar diameter) embedment length was about 50% to 70% of that with $5d$ embedment length. Wardeh *et al.* [30] and Jun [23] got the same conclusion. The reasons are following: On the one hand, the voids at the interface between RAC and steel bar increases with the increase of embedment length; On the other hand, the bond stress is distributed along a longer embedded length, resulting in the decrease in bond strength.

However, Wang *et al.* [29] revealed that the bond strength increased with the increase of embedment length. Qiong *et al.* [54], Li *et al.* [25], Ren [26], Cao *et al.* [50] and Wang *et al.* [51] had shown similar conclusion, but Wang *et al.* [51] also point out that the average bond stress decreased with the increase of embedment length, the reason is that the longer the embedment length, the less uniform the bond stress distribution is.

4.5 Aggregate performance

Kim *et al.* [18] observed that the average water absorption and average density of the RCA showed a strong correlation with the bond strength of RAC specimens. The average water absorption and the average density of RCA were obtained with Eq. (11) and Eq. (12), respectively:

$$A_{ave} = \frac{\sum [ew \cdot ra (\%)]}{T} \quad (11)$$

$$\rho_{ave} = \frac{\sum [ew \cdot rd]}{T} \quad (12)$$

Where ew is each coarse aggregate weight; ra is relevant water absorption; rd is relevant density; T is total weight of coarse aggregate.

Figure 9 gives the relationship between the bond strength and the average water absorption, and Figure 10 gives the relationship between the bond strength and the density values. It can be seen that the bond strength decreased with the increase of average water absorption, while it increased with the increase of average density. However, the influence of the RCA on the bond strength was not significant when the concrete compressive strength was high. Kim *et al.* [44] revealed the similar conclusion that the ultimate bond strength decreased and the slippage corresponding to the ultimate bond strength increased with the increase of average water absorption.

Kim and Yun [36] found that the bond strength of RAC was also influenced by the size of the RCA, the bond strength of RAC with smaller RCA size (the maximum RCA size was 20 mm) was higher than that with larger RCA size (the maximum RCA size was 25 mm), the reason is that the

Figure 9: Relationship between bond strength and average water absorption.

Figure 10: Relationship between bond strength and density values.

RCA is round shape, and the segregation is more serious when flowing. Pandurangan *et al.* [57] conducted the influence of RCA after different treatment methods on the behavior of RAC with steel bar through the beam-type experiment. The results showed that the bond strength of RAC specimens depended on the quality of RCA, and the quality of RCA produced by thermal treatment, acid treatment and mechanical treatment was improved. The normalized bond strength of RAC with untreated RCA was lower than that of RAC with the treated RCA. The reason is that more than 89% of the adhered mortar is removed after thermal treatment, acid treatment and mechanical treatment, resulting in a decrease in the water absorption of the RCA. Butler *et al.* [28] reported that the bond strength of RAC with steel bar decreased with the increase of crushing value of RCA, the reason is that the splice strength and the fracture energy of RCA with lower crushing value is higher [58, 59].

4.6 Others

Jun [23], Pour and Alam [37], Wang *et al.* [51] and Qiong *et al.* [54] conducted research regarding the influence of concrete cover depth on the bond strength of RAC with steel bar, the results showed that the bond strength increased with the increase of concrete cover depth. Pour and Alam [37] revealed that the bond strength of RAC specimens with 67.5 mm concrete cover was 50% higher than that with 42.5 mm concrete cover. The reason is that the constraint level of the specimens with larger concrete cover is higher. Qiong *et al.* [54] point out that the bond strength increased significantly when the concrete cover was increased from 2d to 3d, while it almost unchanged when the concrete cover continued to increase. Seara-Paz *et al.* [38] investigated the influence of curing time on the bond strength of RAC specimens, and found that the bond strength of RAC increased significantly from 7 to 28 days, while it almost no increase from 28 to 365 days. Hu *et al.* [60] investigated the influence of concrete age on the bond strength of RAC specimens, and found that the bond strength increased with the increase of concrete age. Jun [23] revealed that the provision of the horizontal stirrups in RAC specimen had no obvious influence on the bond strength.

5 Influence of freeze-thaw cycles and steel bar corrosion on the bond behavior

5.1 Freeze-thaw cycles

Freeze-thaw cycle will affect the performance of concrete, and then affect the bond behavior of concrete with steel bar [19, 61]. Some studies on bond behavior of RAC with steel bar after freeze-thaw cycles have been investigated. Shang *et al.* [62] investigated the bond behavior of RAC under the action of freeze-thaw cycles through pull-out test, and the results showed that the bond strength decreased with the increasing numbers of freezing and thawing cycles (as shown in Figure 11), while the slippage corresponding to the ultimate bond strength increased. Similar conclusions were also observed from the investigated by An *et al.* [63], Lu [64], Cao *et al.* [66, 67], Wang *et al.* [68, 69], Meng [70] and Wang *et al.* [71]. Shang *et al.* [62] revealed that the reason is that the mechanical properties of RAC decreases after freeze-thaw cycles, and the internal structure of RAC become loose [72, 73]. In addition, Cao *et al.* [65] analyzed the reason for the decrease of the bond strength of RAC specimens after freeze-thaw cycles from microscopic perspective, and point out that the main reason is the frost damage of RAC. Wang *et al.* [68] also reported that the initial slip bond strength (the bond strength when the free end of the steel bar slips) decreased after freezing and thawing cycles due to the internal damage of RAC. Shang *et al.* [74] observed that the influence of freezing and thawing cycles on the bond strength of RAC specimens without air entraining admixture was significantly greater than that with air entraining admixture. Li *et al.* [75] investigated the bond behavior of RAC specimens with different replacement rates of RCA after freeze-thaw cycles, and found that when the number of freeze-thaw cycles was less, the bond strength of RAC specimens was lower than that of NAC specimens. However, with the increase of freeze-thaw cycles, the bond strength of RAC specimens was higher than that of the NAC specimens. Su *et al.* [76, 77] investigated the bond behavior of RAC with steel bar after salt-frost cycles, and found that the bond strength of the RAC specimens in salt solution decreased more quickly and the slippage was larger than that in water.

In addition, Cao *et al.* [67] and Su *et al.* [76] and Liu *et al.* [78] investigated the influence of freezing and thawing cycles on bond stress distribution along with steel bar, and found that the maximum bond stress had a moving trend

Figure 11: Bond strength versus freezing and thawing cycles.

to the free end with the increase of freezing and thawing cycles. This agrees with the findings of Wang *et al.* [69].

5.2 Steel bar corrosion

Several investigations have been performed on the bond behaviour of RAC with corroded steel bar, and the corrosion rate was controlled by the electrochemistry accelerated method. Bin [79], Cao *et al.* [80, 81], Wang *et al.* [82], Zhao [83], Wu [84] and Xiao *et al.* [85] point out that the bond strength of RAC specimens increased first and then decreased as the extent of steel bar corrosion increase, as shown in Figure 12. Bin [79] also demonstrated that the corrosion induced bond strength degradation of RAC specimens was similar to that of NAC specimens [74, 75], while the degradation degree of the bond strength of RAC with corroded steel rebar was much higher than that of NAC with corroded steel rebar. Zhao [83] revealed that the ultimate bond strength of the RAC specimens with stirrups did not change significantly with the increase of the extent of steel bar corrosion. Fernandez *et al.* [52] demonstrated that the bond strength of RAC specimens with uncorroded steel bar was comparable to that of NAC specimens, while the bond strength of RAC specimens with low steel bar corrosion rate was higher than that of NAC specimens. Cao *et al.* [80] conducted a beam-type experiment on the bond behaviour of RAC with corroded steel bar, and the results showed that the failure mode of RAC specimens was splitting failure when the steel bar corrosion rate was 0% and 1%, while it was pullout failure when the steel bar corrosion rate was 9%, and it was pullout-splitting failure when the steel bar corrosion rate was 3% and 6%. Xiao *et al.* [85] observed that the failure mode of RAC specimens was pullout

Figure 12: Bond strength versus steel bar corrosion rate.

failure when the steel bar corrosion rate was small, while it was spitting failure when the steel bar corrosion rate was higher than 1.4%.

However, Dong [88] reported that the bond strength of RAC specimens decreased as the steel bar corrosion rate increase, and it was further supported by the experiment results of Yang [89]. Yang [89] also found that the bond stiffness and the ratio of initial slip bond strength to ultimate bond strength decreased as the steel bar corrosion rate increase.

In addition, Wang [82] studied the influence of steel bar corrosion rate on bond stress distribution along with steel bar, and found that the bond stress at the load end decreased with the increase of the steel bar corrosion rate, while that at the free end increased. This agrees with the findings of Cao [80]. Cao [81] reported that the bond stress distribution along with steel bars became relatively uniform with the increase of the steel bar corrosion rate. Yang [89, 90] had shown similar conclusion. Yang [89, 90] also point out that the maximum bond stress had a moving trend to the free end with the increase of the steel bar corrosion rate, and the bond stress rigidity increased at free end and load end, and it decreased in the range of 0.15-0.85 times the anchorage length.

All the above investigations accelerated the corrosion of steel bars by electrochemical method and shortened the experiment time. But it could not reflect the actual impact of corrosion due to its poor simulation of corrosion modality [92].

Overall, the freeze-thaw cycles and the steel bar corrosion all affected the bond behavior of RAC with steel bar. When freeze-thaw damage and steel bars corrosion reached a certain degree, the bond behavior of RAC with

steel bar deteriorated, which further affected the safety of RAC structure. Therefore, it was necessary to further investigate the bond behavior of RAC with steel bar, and find out the methods to prevent the bond behavior from deteriorating. In addition, with the development of graphene technology [93, 94], scholars have found that graphene was beneficial to improve the performance of concrete. In the future research, graphene can be used to improve the durability of RAC specimens.

6 Conclusions

This paper presented an overview of bond behavior of RAC with steel bar, which could draw the following conclusions:

- (1) The failure modes RAC specimens is similar to that of NAC specimens. The failure modes of RAC specimen are not only influenced by a single factor. It is necessary to comprehensively consider the influence of various factors on the failure modes of RAC specimen. The steel bar diameter, the concrete cover to diameter ratio and the replacement rate of RCA all affect the load-slip curve of RAC specimen.
- (2) Bond strength predictive equations of RAC with steel bar has been summarized to ensure engineers to better understand their applicability. Comparisons between different bond strength predictive equations of RAC with steel bar show that only one factor (concrete compressive strength) is taken into account in all bond strength these predictive equations, and the stirrup is not considered in those bond strength predictive equations, so it is necessary to be further investigated.
- (3) Bond-slip relationship models of RAC with steel bar is summarized to ensure engineers to better understand their applicability. There is still no uniform regulation for the selection of the values of parameter a and b , and the influence of some factors, such as the concrete cover depth, the embedded length and the stirrup on parameter a and b have not been investigated, and it is necessary to be further investigated.
- (4) Over 30 existing literature are collected to investigated the influencing factors of the bond behavior of RAC specimens, and the critical influencing factors including replacement rate of RCA, concrete compressive strength, steel bar type and steel bar diameter, steel bar embedment length, aggregate performance.
- (5) The bond degradation of RAC specimens after freeze-thaw cycles and steel bar corrosion are presented

respectively. The freeze-thaw cycles and the steel bar corrosion all affect the bond behavior of RAC with steel bar. When freeze-thaw damage and steel bars corrosion reach a certain degree, the bond behavior of RAC with steel bar deteriorate, which further affect the safety of RAC structure.

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