International Journal of Concrete
Structures and Materials

RESEARCH

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Experimental Study on the Property and Mechanism of the Bonding Between Rubberized Concrete and Normal Concrete

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Abstract

Scholars have studied the impact of rubber particles (RPs) on the performance of the concrete and the research topics have covered all the mechanical properties and durability of normal concrete (NC). Recently, scholars have turned their research interest to the structural properties of concrete. However, there are few experimental studies on the bonding properties of RC to NC. The RPs have both positive and negative impacts on the bond performance. On one hand, RPs can reduce the shrinkage of concrete, resulting in reduced shear stress and tensile stress near the bonding boundary. On the other hand, RPs cause a reduction in the overall strength of concrete, resulting in the poor mechanical performance of the interface transition layer between the two concrete. The test results of this study show that the bonding splitting tensile strength between freshly mixed RC to aged NC first increases and then decreases with the rise of the RPs content in the RC, and the bonding splitting tensile strength reaches the peak when the RPs content is 10%. The bonding splitting tensile strength between the NC and the RC mixed with 3–5 mm RP is higher than that between the NC and the RC mixed with 1–3 mm RPs. When mixed with modified RPs, the bonding splitting tensile strength between the RC and the NC is improved. Applying an interfacial agent (a cement slurry or an epoxy) on the old concrete bonding surface can significantly improve the bonding splitting tensile strength. The results of non-repeated two-way ANOVA show that the content of the RPs and the type of the interfacial agent have significant effects on the bond splitting tensile strength, while the size and modification of the RPs have no significant effects on the bond splitting tensile strength.

Keywords: bonding between the old and the new concrete, bonding splitting tensile strength, rubberized concrete, rubber particles

1 Introduction

In the early 1990s, Eldin and Senouci developed rubberized concrete (RC) by replacing part of the aggregate of normal concrete (NC) with rubber particles (RPs) that were made from old car tires (Eldin & Senouci, 1993, 1994). They found that the failure mode of the concrete changed from brittle failure to ductile and plastic failure

with the addition of RPs. In addition, RC can absorb higher plastic energy under compression and tensile loading compared with NC. Since then, researchers have studied the impact of RPs on the performance of the concrete utilized in civil engineering, road engineering, and bridge and water engineering, etc. The research topics have covered all the mechanical properties and durability of NC (Strukar et al., 2019). The results show that RPs has significantly improved the deformation performance, durability, and energy dissipation capacity compared with NC. Therefore, RC has a broad application prospect.

In order to make the rubber concrete in the actual project to get a good application, some scholars have turned

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their research interest to the structural properties of RC. Romanazzi et al. (2021) studied the bond-slip behavior between RC and deformed steel bars. Liu et al. (2011) investigated the influence of RPs on the corrosion resistance of reinforced concrete beams and the behavior of the beams after being corroded via electrical accelerated corrosion. Mendis et al. (2017) and Ismail and Hassan (2017) examined the flexural performance of reinforced RC beams. Xue and Shinozuka (2013) researched the seismic performance of RC columns. Son et al. (2011) discussed the influence of RPs on the deformation capacity and energy absorption capacity of concrete columns. The above researches have proved that RPs can improve the decay resistance, bending deformation performance, and seismic performance of reinforced concrete structures, which provide a wealth of data for the utilization of RC in engineering application. However, to the best of our knowledge, the bond performance between RC and NC has not been studied yet. Like the bonding between RC and steel bars, the bonding between RC and NC is critical when RC is put into application. Therefore, it is necessary to research the bond performance between RC and NC.

Under the influence of human activities and weathering, concrete structures will have different degrees of aging and damage (Guo et al., 2021; Kurihashi et al., 2021; Xargay et al., 2021), which make the maintenance and reinforcement of concrete structures become a special engineering profession. The enlarge section method, pouring new concrete on the old concrete, is the most commonly used approach for reinforcing damaged concrete structures. The key to the success of reinforcement is the bond performance between the new and the old concrete (He et al., 2017; Rashid et al., 2020). Numerous experimental researches have been carried out on the macroscopic mechanical properties of the bonding between the new and the old concrete. The results show that the surface roughness of the old concrete, interfacial agents, and concrete materials are the main factors affecting the interfacial bond strength. Vaysburd et al. (2001) and coworkers' research (2001) shows that the bond strength between the new and the old concrete with a surface chisel treatment is higher than that without the treatment. In general, the greater the roughness of the bonding surface of the old concrete, the better the bonding property. However, when the roughness exceeds a certain control value, the influence of the roughness on the bond performance significantly weakens (Austin et al., 1995). Besides, the bonding strength between the new and the old concrete can also be improved by applying an appropriate interfacial agent. The improvement of the bonding strength, however, varies with the type of interfacial agent (Li, 2003). Moreover, the strength of the old concrete is critical to strong bonding between the new and the old concrete (Climaco & Regan, 2001). Otherwise, even with a strong new concrete support structure, damages will still occur within the old concrete side. Compared with the old concrete, the new concrete has a larger shrinkage, which induces shear stress and tensile stress near the boundary of the bonding interface (Bijen & Salet, 1994). Hence, reducing the shrinkage of the new concrete can improve the bonding strength between the new and the old concrete (Chen et al., 1995).

At present, the researches on the bonding mechanism between the new and the old concrete are mainly carried out on the microstructure of bonding models. Gibergues et al. (1993) investigated the microstructure of a bond interface by using scanning electron microscopy (SEM). The results show that the chemical components in cement, especially sulfates, play a critical role in the formation of the microstructures in the bonding zone. Based on the microstructure analysis of the bonding interface, Li et al. (1999) concluded that the transition layer of the bonding interface between the new and the old concrete can be divided into three sublayers: a permeable layer, a strong effect layer, and a weak effect layer. The permeable layer is located at the old concrete side, which is mainly formed by ions, including Na^+, K^+, SO_4^{2-}, and Ca_2^+. These ions come from the new concrete side through water film infiltration. The strong effect layer consists of a thick layer of directional calcium hydroxide and ettringite crystals and burr-like C–S–H gel. This layer is rich in chemical compounds, pores, cracks, and water films. The weak effect layer is a gradual transition area from the strong effect layer to the new concrete. Generally, the crystal structure in this layer is the same as the new concrete body, and the thickness of this layer is about 5–10 μm.

When an RC slurry is used to bond with an old NC surface, RPs have both constructive and destructive effects on the bonding performance. On one hand, RPs can reduce the shrinkage of the RC, which is beneficial to reduce the shear stress and tensile stress near the bonding boundary. On the other hand, RPs reduce the overall strength of the RC, and the RPs become defects in the interface between the new and the old concrete, which reduces the mechanical strength of the interface transition layer. As RPs can also change the mesostructure of the bonding layer between the new and the old concrete, the bonding performance and mechanism between an RC structure and an NC structure is fundamentally different from that between two NC structures. With an in-depth knowledge of the material and structural properties of RC, RC is entering the commercial application stage. Understanding the binding properties between RC and NC becomes increasingly critical.

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Table 1 Cement properties.

Setting time		Compressive strength		Flexural strength	
Initial	Final	3 days	28 days	3d ays	28 days
169 min	290 min	25.7 MPa	42.3 MPa	6.3 MPa	9.0 MPa

(a)   (b)

Fig. 1 Photographs of the RPSs with a diameter of **a** 1−3 mm and **b** 3−5 mm.

Fig. 2 Grading curves of the river sand and the two types of RPs.
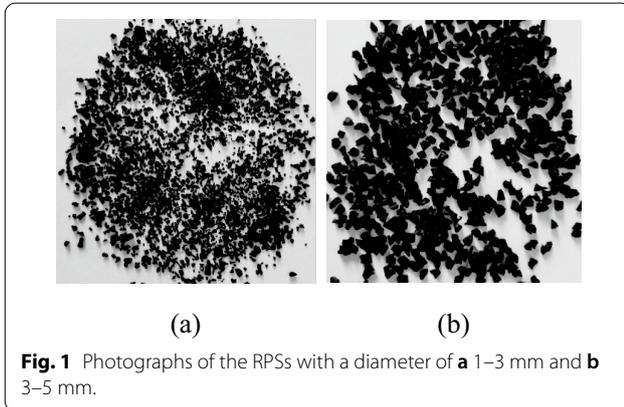
2 Materials and Methods

2.1 Materials

Portland cement 42.5 was used in this research and its properties are listed in Table 1. The coarse aggregate is limestone gravel and the fine aggregate is natural river sand and two types of RPs: 1−3 mm in diameter and 3−5 mm in diameter (Fig. 1). The RPs, made from crushed car tires, have a clean, angular surface. The properties of the coarse and fine aggregates are listed in Table 2. The grading curves of the river sand and two types of RPs are shown in Fig. 2.

A commercial cement paste and a modified epoxy were selected as interfacial agents. The water–cement ratio of the cement paste should be lower than that of the RC (0.54, as shown in Table 3 below) to ensure a better bond strength at the interface. Therefore, the water–cement ratio of cement paste is set to be 0.4 in this study. The modified epoxy mainly composed of epoxy.

The RPs used in this study are made from scrap car tires through mechanical crushing. Numerous additives, such as carbon black, zinc oxide, and aromatic compounds, are added to car tires to improve their durability, ground grip performance, and puncture resistance. These additives exposed on the surface of the RPs weaken the bonding force between the RPs and cement matrix, thus harming the strength of the obtained RC. Therefore, a composite modification method has been developed to remove carbon black and zinc stearate (the reaction product of zinc oxide and stearic acid) of RPs. This modification improves the adhesion between RPs and cement matrix (Khern et al., 2020; Liu et al., 2016; Segre et al., 2002; Youssf et al., 2016). The general process of this method is described as follows: firstly, RPs are soaked in 1% NaOH solution for 24 h; then, the soaked RPs are washed with water until a neutral pH is obtained. After being dried, the RPs are fully wetted by anhydrous ethanol diluted KH570 solution (the weight of KH570 is 1% of the RPs weight); finally, the rubber is dried in the shade.
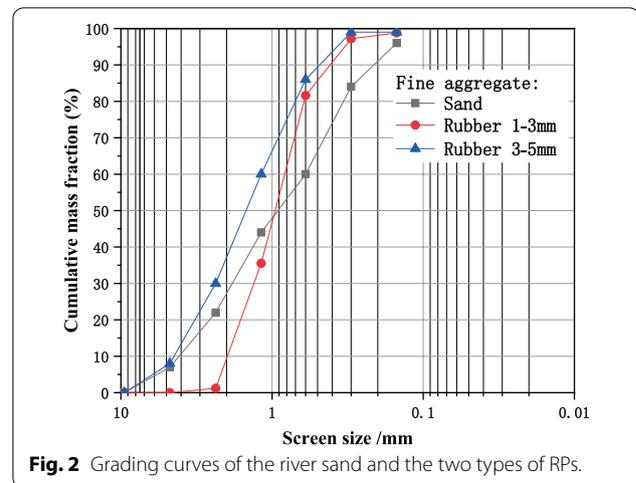
2.2 Mixing

To ensure the same volume fraction of the fine aggregate for all testing samples, the total volume of the sand and the RPs in the PC samples are the same as that of the NC (C30-0 in Table 3). The RPs contents (volume percentage of RPs in the total volume of the fine aggregate) of the RC samples: C30-5, C30-10, C30-15, C30-20, C30-30 are 5%, 10%, 15%, 20%, and 30%, respectively.

Table 2 Aggregate properties.

Material	Size (mm)	Apparent density (kg/m³)	Mud content (%)	Crushed index (%)	Fineness modulus	Elasticity modulus (MPa)	Water absorption
Coarse aggregates	5~20	2688	0.34	8.2	–	16,000	0.3
Fine aggregates	0~4.75	2574	1.1	–	2.9	60	0.3
RPs	1–3 mm, 3–5 mm	1119	0	–	–	6	0.16

Table 3 Recipes of the concrete (unit: kg/m^3).

Mixtures	Water	Cement	Crushed stones	Sand	RPs	RPs volume fraction
C30-0	190	350	1180	680	0	0%
C30-5	190	350	1180	646	14.4	5%
C30-10	190	350	1180	612	28.7	10%
C30-15	190	350	1180	578	43.1	15%
C30-20	190	350	1170	544	57.4	20%
C30-30	190	350	1170	476	86.1	30%

(a) Splitting tensile strength test of concrete

(b) Drawing of a splitted specimen
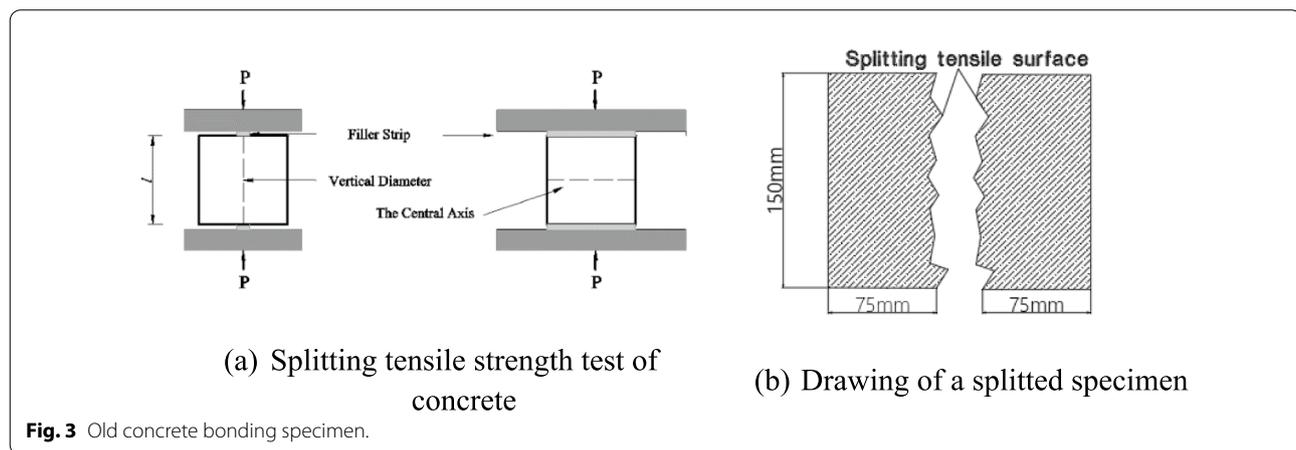
Fig. 3 Old concrete bonding specimen.

2.3 Specimen Preparation and Testing

First, a batch of NC specimens with a size of 150 mm × 150 mm × 150 mm was prepared and conserved in the standard curing room for 28 days (SL352-2006, 2006). After that, the specimens were aged for 60 days under natural conditions. As shown in Fig. 3, according to the splitting tensile strength (SL352-2006, 2006), each aged concrete specimen was split in half to obtain two concrete specimens with a size of roughly 75 mm × 150 mm × 150 mm (Fig. 3b), which will be used as old concrete specimens in the following bonding tests. After loose debris on the split surfaces were removed, the roughness of the split surfaces (referred to as bond surface in the following text) was measured using the sand filling method, as shown in Fig. 4. The average depth of sand filling is taken as the index of the bond surface roughness, and it is calculated using the equation: $H = V/A$ (V is the volume of sand filling and A is the area of the bond surface). The average sand filling depth of the old concrete specimens is 1.106 cm with a standard deviation of 0.238, which indicates that the roughness of the bond surfaces is roughly the same and meets the requirements of the bonding tests (Han et al., 2001).


Fig. 4 Schematic of the sand filling method for measuring the roughness of the bonding surface.
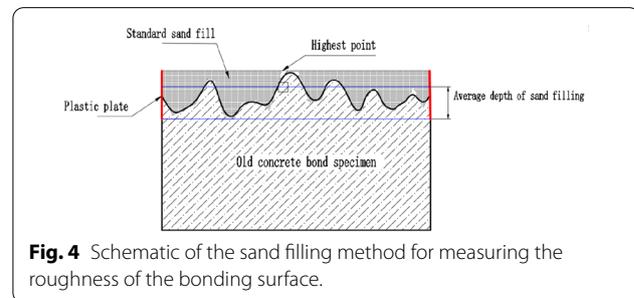
Before pouring freshly mixed RC slurries, the old concrete specimens were soaked in clear water for 1 day. This water saturation process ensures the best performance of the interface agent and the RC slurries, as the old concrete surfaces will not compete with the interface agent and the RC slurries for water. The soaked old concrete specimens were then thoroughly washed and the excess water on the bonding surfaces was removed by a tower, as shown in Fig. 5a. After that, a pre-prepared interface agent was applied on each bonding surface, as shown in Fig. 5b. The optimum thickness of interface agents is 0.5—1.5 mm (Guan et al., 1994). The

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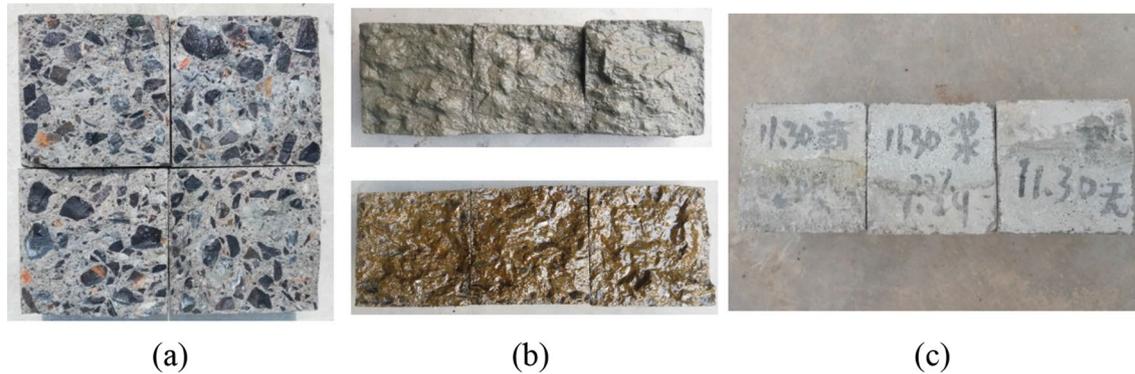
Fig. 5 Bonding specimen preparation process: **a** cleaned old concrete bonding surfaces; **b** interface agent-treated bonding surfaces; **c** bonding specimens.

Fig. 6 Photograph of the splitting tensile strength test setup for bonding tensile strength analysis.

binding performance decreases when the thickness of interface agents exceeds 3 mm(Wall & Shrive, 1988). Next, old concrete specimens coated were placed on 150 mm × 150 mm × 150 mm molds with the bonding surfaces facing up, and various freshly mixed RC slurries were poured into the molds and vibrated to minimize the bug holes. After being hardened for 48 h (as shown in Fig. 5c), the molds were removed, and the bonding specimens were placed in a standard curing chamber for 28 days.

The bonding tensile strength between the RC and the NC of each bonding specimen was analyzed by the splitting tensile strength test of concrete, as shown in Fig. 6. Besides, the compressive strength and splitting tensile strength (referred to as body strength) of an NC specimen and an RC specimen were also obtained using the same testing method. Both specimens are 150 mm × 150 mm × 150 mm in size and have been

cured for 28 days. Prepare 3 specimens for each group, repeat the test for 3 times, and take the average value as the final test result.

3 Results and Discussion

3.1 Influence of the New Concrete Strength on the Bonding Splitting Tensile Strength

3.1.1 Influence of the PR Content in the RC

As shown in Fig. 7 (a), with the increase of the PC content in RPs, the bonding splitting tensile strength between the new and the old concrete first increases and then decreases. The bonding splitting tensile strength between the RC with 5% of RPs and the old NC is lower than that between the RC with 0% of RPs (new NC) and the old NC. This is due to the decrease of the compressive strength and the splitting tensile strength of the RC (Climaco & Regan, 2001). With rich carbon powder and zinc stearate on the surface of the rubber particles, the bonding between the rubber particles and cement stone is poor (Eldin & Senouci, 1993, 1994; Fattuhi & Clark, 1996; Ganjian et al., 2009; Khatib & Bayomy, 1999; Taha et al., 2008; Toutanji, 1996), resulting in a negation correlation between the strength of the RC and RPs content (as shown in Fig. 7c). However, when the content of RPs is 10%, the bonding splitting tensile strength between the RC and the old NC increases by 6.3% (1–3 mm RPs) and 12.5% (3–5 mm RPs) compared with that between the new and the old NC. This indicates the shrinkage of the RPs with 10% of RPs is significantly reduced, resulting in reduced shear stress and tensile stress near the boundary between the new and the old concrete, which improves the bonding splitting tensile strength. However, with the further increase of the RPs content, the decrease in the strength of the RC dominants the trend of the variation of the bond splitting tensile strength between the new and the old concrete. Besides, as the strength of the RC
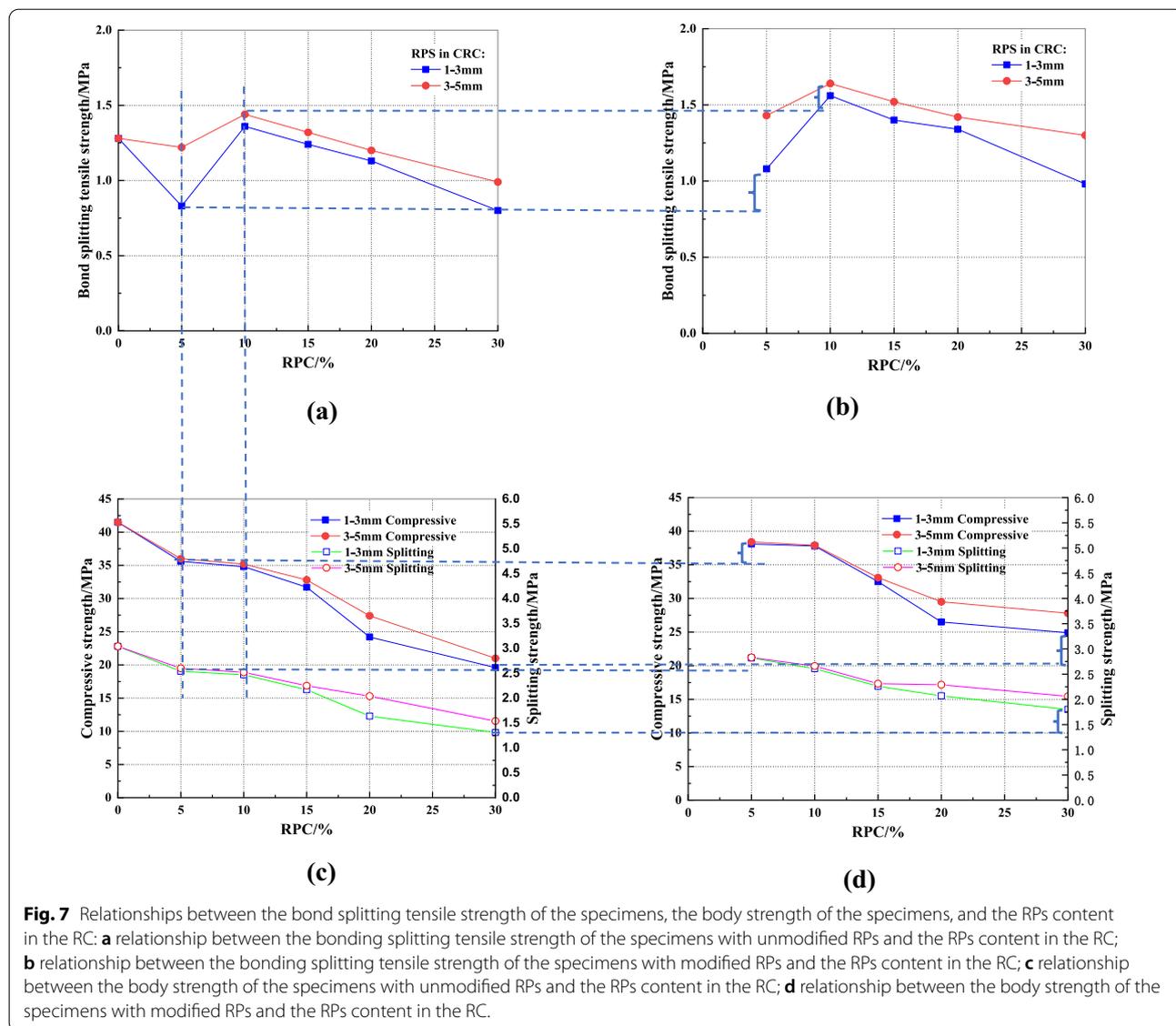
Fig. 7 Relationships between the bond splitting tensile strength of the specimens, the body strength of the specimens, and the RPs content in the RC: **a** relationship between the bonding splitting tensile strength of the specimens with unmodified RPs and the RPs content in the RC; **b** relationship between the bonding splitting tensile strength of the specimens with modified RPs and the RPs content in the RC; **c** relationship between the body strength of the specimens with unmodified RPs and the RPs content in the RC; **d** relationship between the body strength of the specimens with modified RPs and the RPs content in the RC.

is significantly decreased, the cleavage and tensile failure of the bonding specimens occurs on the new RC side. As shown in Fig. 8, the interfacial agent is completely on the old concrete side.

3.1.2 Influence of the RP Size
As shown in Fig. 7(a), the bonding splitting tensile strength between the old NC and the new RC mixed with 3–5 mm unmodified RPs is greater than that between the old NC and the RC mixed with 1–3 mm unmodified RPs. This is mainly due to the higher body strength (compressive strength and splitting tensile strength) of the RC mixed with 3–5 mm unmodified RPs compared with

Fig. 8 Relationship between the bond splitting tensile strength and the RPs content in the RC.

that of the RC mixed with 1–3 mm unmodified RPs (see Fig. 7(c)). With the same RPs volume, the larger the RPs particle size is, the fewer the particle number is. Thus, the negative effect on the body strength of concrete is smaller. On the contrary, the smaller the rubber particle size is, the greater the negative impact on the strength of concrete is.

3.1.3 Influence of the Rubber Particle Modification

As shown in Fig. 7 (c-d), the body strength of the RC with modified RPs is higher than that of the RC with unmodified RPs: when the RPs content is 5%, the compressive strength of the RC with modified RPs is 7.0% (1–3 mm RPs) and 6.7% (3–5 mm RPs) higher than that of the RC with unmodified RPs; when the RPs content is 30%, the compressive strength of the RC with modified RPs is 27.0% (1–3 mm RPs) and 32.4% (3–5 mm RPs) higher than that of the RC with unmodified RPs; when the RPs content is 5% RPs, splitting tensile strength of the RC with modified RPs is 11.0% (1–3 mm RPs) and 2.3% (3–5 mm RPs) higher than that of the RC with unmodified RPs; when the RPs content is 30%, the compressive strength of the RC with modified RPs is 37.4% (1–3 mm RPs) and 33.8% (3–5 mm RPs) higher than that of the RC with unmodified RPs. The improvement in the body strength of the RC induces the bond splitting tensile strength between the RC and the NC, as shown in Fig. 7(a, b): when the rubber particle content is 5%, the bond splitting tensile strength of the specimen with modified RPs is 30.1% (1–3 mm RPs) and 17.2% (3–5 mm RPs) higher than that of the specimen with unmodified RPs; when the rubber particle content is 30%, the bond splitting tensile strength of the specimen with modified

RPs is 22.5% (3–5 mm RPs) and 31.3% (3–5 mm RPs) higher than that of the specimen with unmodified RPs.

3.2 Influence of the Interfacial Agent on the Bond Splitting Tensile Strength

It can be seen from Fig. 9 that applying an interfacial agent (a cement paste or a modified epoxy) on the bonding surfaces of old concrete specimens can significantly improve the bonding splitting tensile strength between the new and the old concrete. The bonding splitting tensile strength of the specimens with the epoxy interfacial agent is higher than that of the specimens with the cement paste interfacial agent or without an interfacial agent. Compared with the specimens without an interfacial agent and with the cement paste interfacial agent, the bonding splitting tensile strength between the new NC and the old NC is significantly improved by the cement paste interfacial agent, while the bonding splitting tensile strength between the new RC and the old NC is only slightly enhanced by the cement paste interfacial agent. For the specimens of a new NC bonded to an old NC, the bonding splitting tensile strength of the specimen with the cement paste interfacial agent is 71.8% higher than that of the specimen without an interfacial agent. For the specimens of a new RC bonded to an old NC, the bonding splitting tensile strength of the specimen with the cement paste interfacial agent is 7.1–40.4% (1–3 mm RPs) and 5.7–13.8% (3–5 mm RPs) higher than that of the specimen without an interfacial agent. When comparing the specimens the cement slurry interfacial agent with the specimens with the epoxy interfacial agent, the bond splitting tensile strength between the new NC (RPs content = 0) and the old NC is increased by 13.6%, and
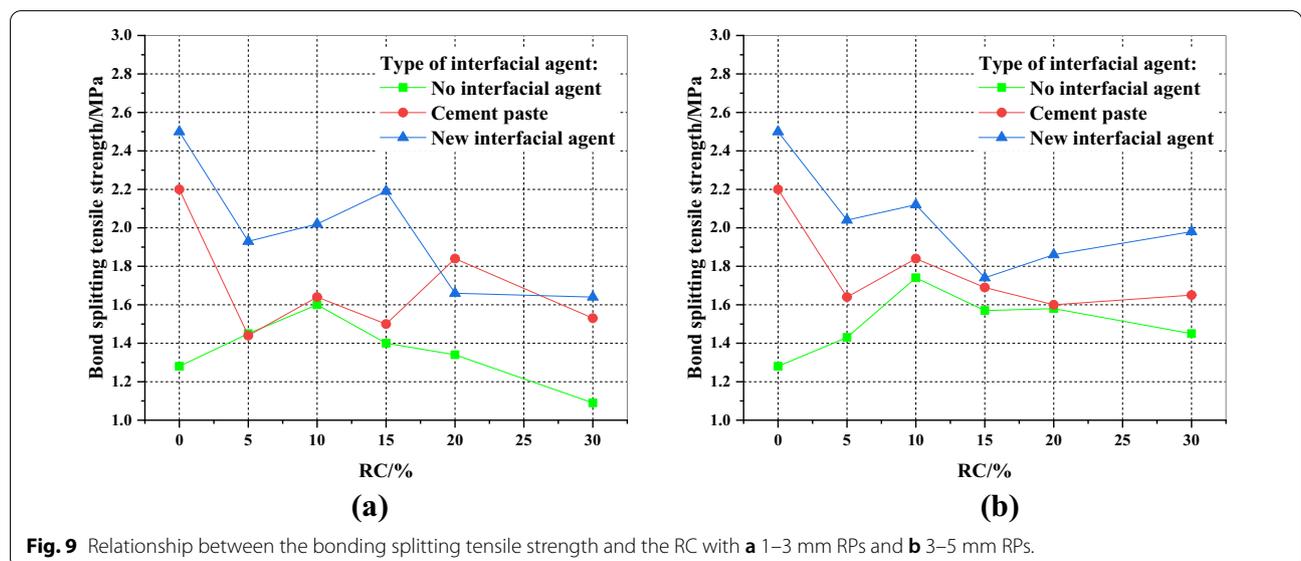
Fig. 9 Relationship between the bonding splitting tensile strength and the RC with **a** 1–3 mm RPs and **b** 3–5 mm RPs.

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the bond splitting tensile strength between the RC and the old NC is improved by 7.2–40.0% (1–3 mm RPs) and 3.0–24.4% (3–5 mm RPs). In summary, the epoxy interface agent works better than the cement paste in improving the bonding splitting tensile strength between the new and the old concrete. Besides, the interfacial agents working better with the RC with 3–5 mm RPs than the RC with 1–3 mm RPs.

3.3 Significance Analysis of the Factors Influencing the Bonding Splitting Tensile Strength

In this paper, the factors that affect the bonding splitting tensile strength between the new and the old concrete include the surface modification, the RPs content, the size of the RPs, and the interface agent. The influence of each factor on the bonding splitting tensile strength of a specimen is different. In this study, a non-repeated two-factor ANOVA was employed to quantitatively analyze the influence of each factor.

In an experiment, if factor A has r levels: A_1, A_2, ..., A_r and factor B has s levels: B_1, B_2, ..., B_S, a test with a pair of A and B, (A_i, B_j), is called two-factor equal-repeated variance analysis. The data table is as follows: (Table 4).

In this analysis, two basic assumptions are: (1) X_{ij} are mutually independent, (2) $X_{ij} \sim N(\mu_{ij}, \sigma^2)$.

The following parameters can be calculated based on the above data table:

The mean of all the observed values is

$$\overline{X} = \frac{1}{rsn} \sum_{i=r}^{r} \sum_{j=1}^{s} \sum_{k=1}^{n} X_{ijk}. \tag{1}$$

The mean under the condition of (A_i, B_j) is

$$\overline{X_{ij.}} = \frac{1}{n} \sum_{k=1}^{n} X_{ijk}. \tag{2}$$

The mean under the condition of A_i is

Table 4 Datasheet of the two-factor equal-repeated variance analysis.

	B$_1$	B$_2$	...	B$_s$
A$_1$	X$_{111}$	X$_{121}$	...	X$_{1s1}$
	...	...		...
	X$_{11n}$	X$_{12n}$		X$_{11n}$
A$_2$	X$_{211}$	X$_{221}$	...	X$_{2s1}$
	...	...		...
	X$_{21n}$	X$_{22n}$		X$_{2sn}$
A$_r$	X$_{r11}$	X$_{r21}$	...	X$_{rs1}$
	...	...		...
	X$_{r1n}$	X$_{r2n}$		X$_{rsn}$

$$\overline{X_{i..}} = \frac{1}{sn} \sum_{j=1}^{s} \sum_{k=1}^{n} X_{ijk}. \tag{3}$$

The mean under the condition of B_j is

$$\overline{X_{.j.}} = \frac{1}{rn} \sum_{i=1}^{r} \sum_{k=1}^{n} X_{ijk}. \tag{4}$$

The sum of the squared deviation of factor A (r-1 degrees of freedom) is

$$S_A = sn \sum_{i=1}^{r} (\overline{X_{i..}} - \overline{X})^2. \tag{5}$$

The sum of the squared deviation of factor B (s-1 degrees of freedom) is

$$S_B = rn \sum_{j=1}^{s} (\overline{X_{.i.}} - \overline{X})^2 \tag{6}$$

The sum of the squared deviation of A × B is

$$S_{AB} = n \sum_{i=1}^{r} \sum_{j=1}^{s} (\overline{X_{ij.}} - \overline{X_{i..}} - \overline{X_{.j.}} + \overline{X})^2. \tag{7}$$

Its degree of freedom is (r-1)(s-1).
The sum of squared errors is

$$S_E = \sum_{i=1}^{r} \sum_{j=1}^{s} (X_{ij} - \overline{X}_{i.} - \overline{X}_{.j} + \overline{X})^2. \tag{8}$$

Its degree of freedom is rs(n-1).
The sum of the total squared deviations is

$$S_T = \sum_{i=1}^{r} \sum_{j=1}^{s} (X_{ij} - \overline{X})^2, \tag{9}$$

$$S_t = S_A + S_B + S_E. \tag{10}$$

Its degree of freedom is rsn-1.
The sum of the mean squared deviation of factor A is

$$MS_A = S_A/(r-1). \tag{11}$$

The sum of the mean squared deviation of factor B is

$$MS_B = S_B/(s-1). \tag{12}$$

The sum of the mean squared deviation of factor A × B is

$$MS_{AB} = S_{AB}/(r-1)(s-1). \tag{13}$$

The sum of the mean square errors is

$$MS_E = S_E / rs(n - 1). \tag{14}$$

Hence,

$$F_A = MS_A / MS_E \sim F((r - 1), rs(s - 1)), \tag{15}$$

$$F_B = MS_B / MS_E \sim F((s - 1), rs(s - 1)), \tag{16}$$

$$F_{AB} = MS_{AB} / MS_E \sim F((r - 1)(s - 1), rs(s - 1)). \tag{17}$$

For a given test level α, when $F_A > F_a((r - 1), rs(s - 1))$, the influence of factor A has statistical significance; when $F_B > F_a((s - 1), rs(s - 1))$, the influence of factor B has statistical significance; when $F_{AB} > F_a((s - 1), rs(s - 1))$, the influence of factor A × B has statistical significance.

Firstly, the significance of the influence of the RP content (A) and the type of interfacial agent (B) on the bond splitting tensile strength was analyzed. Factor A has A_r (r = 1,2,3,4,5,6) levels and factor B has B_s (s = 1,2,3) levels. For each A and B pair, (A_i, B_j), the experimental value, X_{ijk} (I = 1, 2, ..., r; J = 1, 2, ..., s; K = 1, 2, ..., n) can be obtained. Here, the repeated test number, n, is 3. The test results of bond splitting tensile strength between the old NC and the new RC mixed with 1–3 mm RPs were analyzed as an example. The calculated F values are F_A = 9.001 and F_B = 14.898.

Here, F_A = 9.001 > $F_{0.005}(5,36)$ = 2.50, F_B = 14.898 > $F_{0.005}(2,36)$ = 3.28.

These results indicate that at a significance level of 0.05, both RP content (A) and type of interfacial agent (B) have statistical significance on the bond splitting tensile strength.

Next, the RPs size (A) and the RPs content (B) were also analyzed by the two-factor equal-repeated variance analysis to examine the significant level of the two factors on the bond splitting tensile strength. Factor A has A_r (r = 1,2) levels and factor B has B_s (s = 1,2,3,4,5,6) levels. For each A and B pair, (A_i, B_j), the experimental value X_{ijk} (I = 1,2, ..., R; J = 1, 2, ..., s; K = 1, 2, ..., n) can be obtained, and the repeated test number, n, is 3. Taking the test results of splitting tensile strength of bonding specimen with the epoxy interfacial agent as an example, the calculated F values are F_A = 3.123 and F_B = 9.133.

Here, F_A = 3.123 < $F_{0.005}(1,24)$ = 4.26, F_B = 9.133 > $F_{0.005}(5,24)$ = 2.62.

This indicates that at a significance level of 0.05, the RPs size (A) has no statistical significance on the bond splitting tensile strength, while the RPs content (B) has statistical significance on the bond splitting tensile strength.

Lastly, the two-factor equal-repeated variance analysis was conducted to analyze the significance level of the RPs modification (A) and the RPs content (B) on bond splitting tensile strength. Taking the test results of adhesive splitting tensile strength of the bonding specimens with 1–3 mm RPs and the epoxy interfacial agent as an example, the calculated F values are F_A = 0.105 and F_B = 7.461.

Here, F_A = 0.105 < $F_{0.005}(1,24)$ = 4.26, F_B = 7.461 > $F_{0.005}(5,24)$ = 2.62.

These results indicate that at a significance level of 0.05, the RPs modification condition (A) has no statistical significance on the bond splitting tensile strength, while the RPs content (B) has statistical significance on the bond splitting tensile strength.

In summary, the content of RPs and the type of interfacial agent have significant effects on the bond splitting tensile strength, while the RPs size and the RPs modification have no significant effects on the bond splitting tensile strength.

4 Bonding Mechanism Analysis

As the cement hydration reaction in old concrete specimens has been completed before bonding to a new concrete slurry, van der Waals force and mechanical meshing force are the main bonding force between the new and the old concrete, and these bonding forces are weak. In addition, the volume of the new concrete shrinks during the hardening process. Due to the constraint effect of the old concrete, shear stress and tensile stress are generated at the bonding interface, and shrinkage microcracks are developed in the bonding transition layer, resulting in reduced bonding strength between the new and the old concrete. Through scanning electron microscope imaging and microstructure analysis of the bonding interfaces, it is concluded that the bonding transition layer can be divided into three sublayers: a permeable layer, a strong effect layer, and a weak effect layer, among which the structure of the strong effect layer plays a decisive role in the bonding performance. The permeable layer is located on the old concrete side, and it is mainly formed by Na^+, K^+, SO_4^{2-}, and Ca^{2+}, which come from the new concrete side through water film infiltration. The strong effect layer consists of a thick layer of directional calcium hydroxide and ettringite crystals and burr-like C–S–H gel. This layer is also rich in chemical compounds, pores, cracks, and water films. Due to the water absorption characteristic of the old concrete, a thin layer of water film forms in the old concrete during the bonding process, causing the water–cement ratio at this region to be higher than that in the new concrete body. The high water–cement ratio induces the formation of a large number of loosely packed hydration crystals with large size and preferred orientation. The weak effect layer is a gradual transition area from the strong effect layer to the new concrete. Generally, the crystal structure in this layer is the same as the new concrete body, and the thickness of this layer is about 5 ~ 10 μm.

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Interfacial fracture models can be established based on the characteristics of the fractures between the new and the old concrete and the properties of interfacial materials. These models fall into three categories: (1) when the interface bonding is good and the bonding strength is higher than the crack resistance strength of the interface layer, the cracks that reach the interface will be blocked and retained within the interface layer, resulting in a random wavy fracture along the penetration direction of microcracks in the interface layer. (2) When the interface bonding is good and the bonding strength is close to the crack resistance strength of the interface layer, the cracks that reached the interface will not enter the new and the old concrete bodies in their original directions, and they will expand along with the interface by connecting the microcracks developed within the interface. When the resistance element is encountered, the cracks will turn back to the interface layer and repeat the above development process, resulting in a stepped fracture alternatively passing through the interface and the interface layer. (3) When the interface bonding is poor and the bonding strength is less than the crack resistance strength of the interface layer material, the cracks extending to the interface will develop along with the interface. The development of cracks follows the chain of the weakest points within the interfacial layer, which depends on the bonding quality between the new and the old concrete. The bonding quality of the interface is mainly affected by the roughness of the interface, the type of interface agent, the bonding mode, and the strength of the concrete body.

As shown in Fig. 10, in each photograph, the left one is the new concrete side and the right one is the old NC side. The following observations can be made:

(1) For the specimens without an interfacial agent and with the epoxy interfacial agent, a small number of RPs are observed on the fracture surfaces on the new concrete side, and the fractures within the fresh cement stone are also found. For the specimens with the cement paste interfacial agent, no rubber particles appear on the fracture surface on the new concrete side. It shows that the failure mechanisms of the specimens with cement slurry interfacial agent and the epoxy interfacial agent are different.

(2) For the specimens without an interfacial agent and with the epoxy interfacial agent, the fracture surfaces on the new concrete side have fresh C-S–H gel, while the fracture surface on the old concrete side only shows its original aggregate and cement stone; For the specimens with the cement paste interfacial agent, the interfacial agent and the new cement stone can be observed on both fracture surfaces, indicating the bonding between the new and the old concrete is good.

The image analysis shows that, without an interfacial agent, the strong effect layer is very thin, and the RPs are distributed in both the strong effect layer and the weak effect layer. As fractures occur in the strong effect layer,
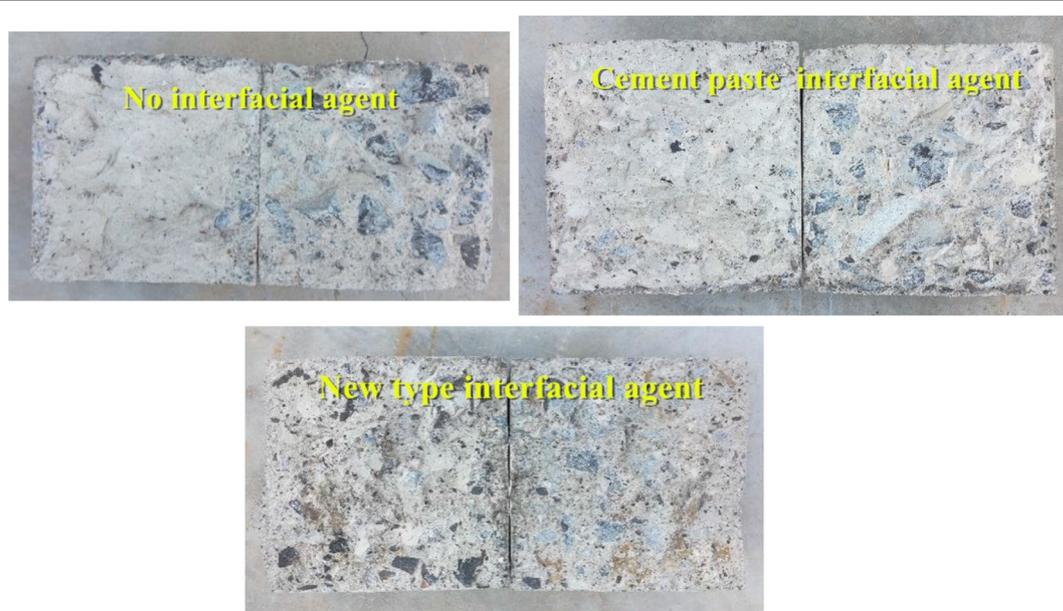

Fig. 10 Fracture surfaces of the bonding specimens.

few RPs can be found on the fracture surface on the new concrete side. When the cement paste is used as the interface agent, the strong effect layer is thick, the rubber particles are mainly distributed in the weak effect layer. As the fractures still occur in the strong effect layer, RPs are not observed in the fracture surface on the new concrete side. Like the specimens with the cement paste interface agent, the specimens with the epoxy interface agent have a thick strong effect layer and RPs are mainly distributed in the weak effect layer. Due to the strong bonding effect of the epoxy interface agent, fractures can be developed in the permeable layer, the strong effect layer, or the weak effect layer, even in the bodies of the new and the old concrete. Hence, a small number of RPs can be found on the fracture surface on the new concrete side.

5 Conclusions

With the increase of the RPs content in the RC, the bonding splitting tensile strength of the specimens first increases and then decreases. The binding splitting tensile reaches the peak value at a RPs content of 10%. The increase of the bonding splitting tensile strength is because of the reduction in the shear stress and tensile stress near the bonding interface, owning to the low dry shrinkage of the RC. The decrease of the bond splitting tensile strength is due to the poor bonding quality of the RC when the RPs content is high. Hence, the failures of the specimens with high RPs content often occur at the RC side. As the body strength (compressive strength and splitting tensile strength) of the RC mixed with 3–5 mm RPs is greater than that of the RC mixed with 1–3 mm RPs, the bonding splitting tensile strength between the old NC and the RC mixed with 3–5 mm RPs is higher than that between the old NC and the RC mixed with 1–3 mm RPs. When mixed with the modified RPs, the body strength of the RC is improved, which directly leads to the increase of the bonding splitting tensile strength.

Applying an interfacial agent (the cement paste or the modified epoxy) on the bonding surface of the old concrete can significantly improve the bonding splitting tensile strength between the new and the old concrete. The specimens treated by the epoxy show 7.2–40.0% (1–3 mm RPs) and 3.0–24.4% (3–5 mm RPs) improvement in the bond splitting tensile strength compared with that treated by the cement slurry.

The quantitative analysis of the influence of the RPs modification, the RPs content, the RPs size, and the interfacial agent was carried out by using the non-repeated two-factor ANOVA. The results show that the RPs content and the type of the interfacial agent have significant effects on the bonding splitting tensile strength, while the RPs size and the RPs modification have no significant effects on the bonding splitting tensile strength.

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