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Rupture probability of coarse aggregate on fracture surface of concrete

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Abstract

In this work, the fracture surface of concrete was analyzed by the digital image analysis (DIA) technique, and the rupture probability of the coarse aggregate (RPCA) was used to represent the failure mode of the aggregate at the fracture surface. The relationships between the RPCA, the water-binder ratio (W/B), and the size and type of coarse aggregate were investigated. Preliminary results showed that: (1) RPCA increases with decreasing W/B of concrete. (2) RPCA of concrete with coarse aggregates having a maximum size of 16 mm is higher than that with other sizes of coarse aggregate. The influence of the size of coarse aggregate on the RPCA is more significant in high strength concrete than in normal strength concrete. (3) With reduction of W/B, the interfacial bond of concrete with crushed gravel improves more significantly than with round gravel according to their RPCA. (4) RPCA depends not only on the intrinsic strength, size, and shape but also on the reactivity of the coarse aggregate.

Keywords: Image analysis; Aggregate; Bond strength; Concrete

1. Introduction

It is well known that the coarse aggregate forms the skeleton of concrete, and its properties to a great degree affect the global properties of the concrete. The effects of the coarse aggregate parameters on the strength and fracture properties of concretes have previously been reported [1–4]. However, there has been very little research on the influence of coarse aggregate based on observations of the fracture surfaces of concrete.

Abundant information about the failure process can be acquired from observation and analysis of the fracture surfaces of concrete [5–7]. This information is of great importance for the fracture analysis of concrete and the failure evaluation of practical projects since the fracture resistance of concrete may be deduced through quantitative analysis of the information. Hence, in this work, an attempt was made to apply the digital image analysis (DIA) technique to analyze the fracture surfaces of concrete. A parameter representing the failure mode of the coarse aggregate, rupture probability of coarse aggregate (RPCA), was proposed and the relationships between RPCA, the water-binder ratio (W/B) of concrete, and the size and type of coarse aggregate were investigated.

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2. Methods

2.1. Raw materials

The cement used was no. 525 ordinary Portland cement (according to GB175-92 of P.R. China), made by the Wusong cement factory (Shanghai, China), with a 28-day compressive strength of 63.5 MPa. The ultrafine slag powder was provided by the Jinshan cement factory of Shanghai, China, and had a Blaine fineness of 600 m^2/kg. The aggregate used had a 2.85 fineness modulus of the fine aggregate. Four different maximum sizes of coarse aggregates were used: 10, 16, 20, and 31.5 mm. Four different types of coarse aggregates were used: crushed basalt (CB), crushed gravel (CG), round gravel (RG), and clinker. The crush index (indirectly reflecting the strength of the aggregate) of crushed gravel, round gravel, and clinker were 8.3, 8.45, and 3.5%, respectively. The roundness (the more nearly roundness approaches to 1.0, the more nearly the coarse aggregate shape approaches that of a sphere) of crushed gravel, round gravel, and clinker were 0.867, 0.911, and 0.931, respectively. The superplasticizer used was a sulphonated naphthalene formaldehyde superplasticizer.

2.2. Mixture proportions

To investigate the relationships between RPCA, W/B of concrete, and the size and type of coarse aggregate, three series of concrete mixtures were designed. The superplasticizer was used to control the workability of the fresh con-

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cretes. The mix proportions of the three series of mixtures are listed in Table 1. CB, CG, and RG designate crushed basalt, crushed gravel, and round gravel, respectively.

2.3. Casting, curing, and testing of specimens

Six 100 × 100 × 100-mm cubes were cast for each concrete mixture and were used for compressive and splitting tensile tests. The specimens were demoulded 1 day after casting, and then were cured in a room in which the temperature ranged from 17 to 23°C and the relative humidity was greater than 90% until they were tested at 28 days.

2.4. Pretreatment and image analysis of the fracture surfaces

Under normal dry conditions, the grey contrast between the coarse aggregates and other parts of the fracture surfaces is too inconspicuous to be fit for analysis by the image analysis system. Therefore, it is necessary to pretreat the fracture surfaces. The method of moderately eroding the fracture surfaces was used. The fracture surfaces of specimens were soaked by a hydrochloric acid solution (the volume ratio of hydrochloric acid to water was 1:4) after the splitting tensile strength test. They were taken out 2 h later and washed and dried.

The coarse aggregates protruded slightly from the fracture surfaces after pretreatment and the borders between the coarse aggregates and hardened cement paste were clear since a film of hardened paste was peeled off. Fig. 1 illustrates one of the fracture surfaces after pretreatment.

The DIA system used in this work is a highly efficient image handling system, which includes an image-producing system, an image-processing system, and an output system. The image-producing system took the optical image of the fracture surface, and then converted it into a grey image. To avoid deterioration of image quality caused by noise during the course of producing, transmitting, and converting the image, we took the following steps to optimize the binary images: (1) enhancing image contrast repeatedly until the coarse aggregate phases were clear; (2) filling holes; (3) using the "opening" operation to delete unwanted objects; and (4) using the "binary edit" operation to modify the measured frame and specify all projections of coarse aggregates.

2.5. RPCA

Normally, when concrete fails, there are two modes of failure of the coarse aggregate: (1) the crack deflects around the aggregates (i.e., debonding of coarse aggregate) or (2) the crack penetrates through the aggregates (i.e., rupture of coarse aggregate).

To study the effects of coarse aggregates on the fracture resistance of concrete, we defined the RPCA as the ratio of the area of ruptured coarse aggregates (RCAA) to the total projected area of coarse aggregates (TCAA), as seen in Eq. (1):

$$\mathrm{RPCA} = \frac{\mathrm{RCAA}}{\mathrm{TCAA}} \tag{1}$$

Two measurements were made on the same fracture surface. First, all the ruptured coarse aggregates on the fracture surface were measured. After selecting the projections of ruptured coarse aggregates on the fracture surface, the image analysis system calculated the length and area of every coarse aggregate, and then counted the area of rupture of the coarse aggregates according to the chosen parameters (length and area in this work). Second, all of the coarse ag-

Table 1
Concrete mix proportions

	Mix proportion (kg/m^3)						Aggregate characteristic	
Series	Cement	Slag	Water	Coarse aggregate	Fine aggregate	W/B	Size of coarse aggregate (mm)	Aggregate type
I								
I11	472	202	175	948	632	0.26	16–31.5	CB
I12	472	202	175	948	632	0.26	5–16	CB
I21	420	180	180	986	657	0.30	16–31.5	CB
I22	420	180	180	986	657	0.30	5–16	CB
I31	267	115	168	1110	740	0.44	16–31.5	CB
I32	267	115	168	1110	740	0.44	5–16	CB
II								
II11	267	115	168	1110	740	0.44	10 (Dmax)	CB
II12	267	115	168	1110	740	0.44	16 (Dmax)	CB
II13	267	115	168	1110	740	0.44	20 (Dmax)	CB
II21	472	202	175	948	632	0.26	10 (Dmax)	CB
II22	472	202	175	948	632	0.26	16 (Dmax)	CB
II23	472	202	175	948	632	0.26	20 (Dmax)	CB
II24	472	202	175	948	632	0.26	31.5 (Dmax)	CB
III								
III11	267	115	168	1110	740	0.44	5–16	CG
III12	267	115	168	1110	740	0.44	5–16	RG
III21	472	202	175	948	632	0.26	5–16	CG
III22	472	202	175	948	632	0.26	5–16	RG
III23	472	202	175	582	632	0.26	5–16	Clinker

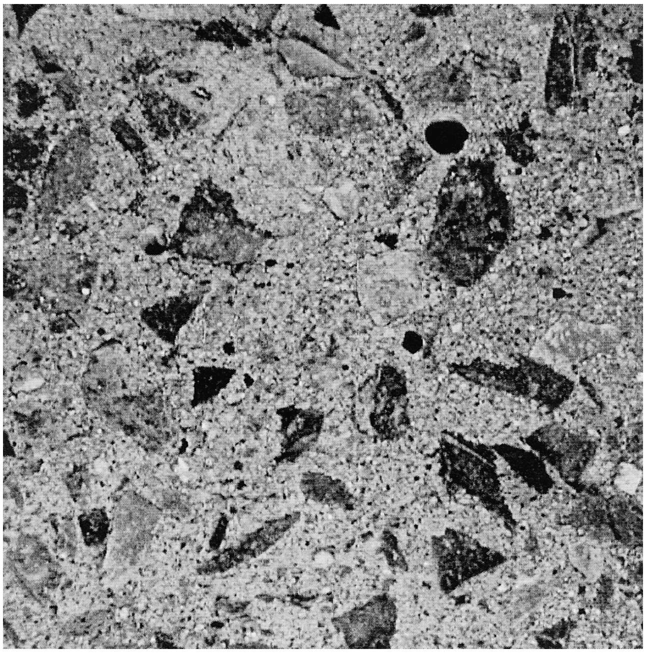

Fig. 1. Fracture surface after pretreatment.

gregates on the fracture surface were measured in the same way as in the first step. Some holes may appear on the fracture surface because of debonded aggregates, which makes the actual TCAA decrease. Hence, areas of debonded aggregates on the corresponding surface will compensate the TCAA on one fracture surface. For each specimen, six fracture surfaces were measured. Then the mean values of TCAA and RCAA for every kind of concrete were computed. Using the above formulation, the value of RPCA was obtained.

3. Results and discussion

The relationship between W/B and RPCA for series I is illustrated in Fig. 2. It can be seen that regardless of the size of coarse aggregate, the RPCA of concrete decreases with increasing W/B. In other words, on the fracture surfaces of concrete, with increasing W/B, more and more coarse aggregates debond while the number of ruptured coarse aggregates decreases.

Fig. 3 shows the relationship between RPCA and aggregate size for W/B ratios of 0.44 and 0.26 (for series II). It was found that regardless of W/B, with an increase in the maximum size of coarse aggregate from 10 to 16mm, RPCA increases, but from 16 to 31.5 mm, RPCA decreases. Furthermore, it was observed that the influence of the size of coarse aggregate on the RPCA of the concrete was more significant for high strength (low W/B) concrete than for normal strength (high W/B) concrete.

At different W/B ratios, different types of coarse aggregate result in different RPCA values (Fig. 4). After reducing the W/B from 0.44 to 0.26, crushed gravel showed the highest increment of RPCA by 136.6%, while the RPCA for round gravel increased by only 74.8%. At a W/B of 0.44, concrete with round gravel produced a higher RPCA than crushed gravel by 18.28%, while at the lower W/B of 0.26,

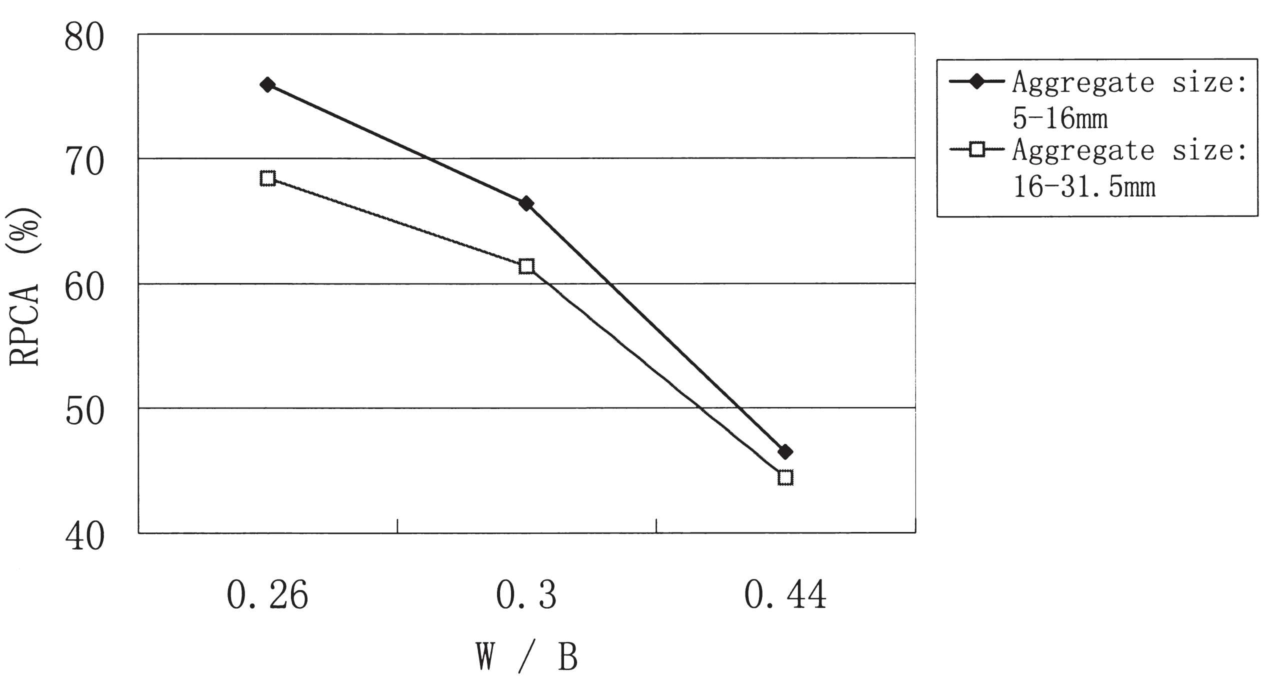

Fig. 2. The relationship between W/B and RPCA for series I.

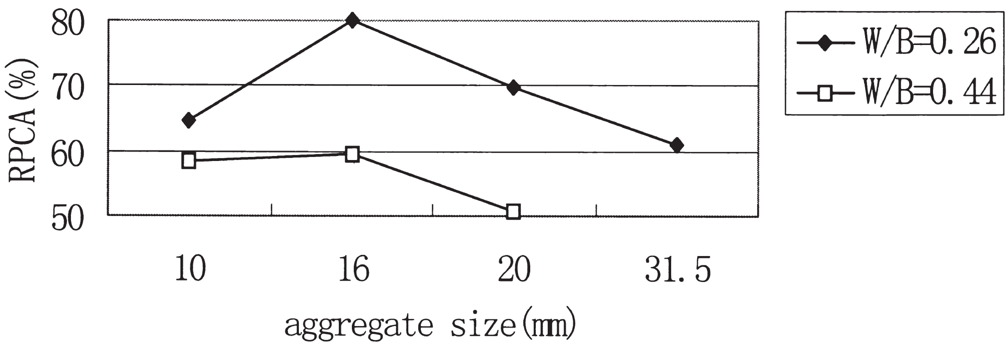

Fig. 3. RPCA vs. aggregate size for series II.

the latter produced a higher RPCA than the former by 14.4%. In addition, the RPCA value of concrete with clinker lies between those of crushed gravel and round gravel.

When concrete is loaded, coarse aggregate is subjected to two kinds of forces: a pull-out force and the intrinsic cohesion of the coarse aggregate. Hence, the relative values of these two forces are responsible for the failure mode of the coarse aggregate. Because both the pull-out force and the intrinsic cohesion of coarse aggregate are directly proportional to the coarse aggregate-matrix interfacial bond strength and the strength of the coarse aggregate, respectively [8], RPCA depends on the interfacial bond strength and the strength of coarse aggregate. Therefore, the factors that influence these two also affect the RPCA.

It is well known that for high W/B concrete, the interfacial zone is weaker than the coarse aggregate. Cracks prefer to propagate along the interfacial zone, while the coarse aggregates debond, and then deflect and bridge cracks. However, the failure mechanism of low W/B concrete is different from that of high W/B concrete, since the quality of the interfacial zone is greatly improved. More cracks pass through the coarse aggregates while the effects of coarse aggregate on bonding, deflecting, and bridging cracks decrease, as was shown in Fig. 1.

The RPCA of concrete with 16-mm coarse aggregate is higher than that of the other sizes used in this study, which reveals the predominant influence of the intrinsic strength of coarse aggregate and interfacial bond strength. In the range of smaller particle sizes (i.e., 10–16 mm), the intrinsic strength of the aggregate may play a paramount role. Hence, with increasing size, the intrinsic defects of the aggregate increase, which reduces the strength of the coarse aggregate, thus increasing the RPCA; while in the range of larger particle sizes (i.e., 16–31.5 mm), the effect of interfacial bond may be more significant. Hence, with increasing size, the vulnerable zone of the coarse aggregate-matrix interface becomes larger, which impairs interfacial bond, thus decreasing the RPCA.

In the terms of the effects of the type of coarse aggregate on interfacial bond strength and RPCA, the similar crushed index values of crushed gravel and round gravel means that the intrinsic strength of these aggregates is similar. Hence, the results in Fig. 3 demonstrate that with decreasing W/B, the interfacial quality of the concrete with crushed gravel improves more significantly than that with round gravel, since rounded gravel more closely approaches a sphere than does crushed gravel. The crush index of clinker is the lowest, so its intrinsic strength is the highest. Therefore it would be expected that the RPCA of concrete made with clinker would be the lowest. But it was found that its RPCA is 76.39%, which is larger than that of round gravel. One possible explanation may be that the interfacial

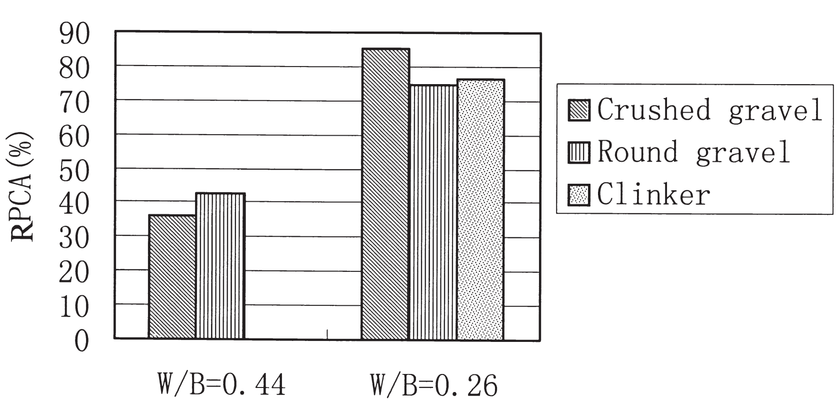

Fig. 4. RPCA and aggregate type for series III.

zone in concrete made with clinker is stronger than that of gravel because of the interfacial chemical reactions between water and clinker. So, RPCA depends not only on the strength, size, and shape but also on the reactivity of the aggregate.

4. Conclusions

In this work, the fracture surfaces of concrete were analyzed by using an advanced DIA technique, and the RPCA was suggested as a parameter to represent the failure mode of aggregates along the fracture surface. The results of this initial investigation indicate:

1. RPCA increases with decreasing W/B of concrete.
2. RPCA of concrete with 16-mm coarse aggregate is higher than for other sizes of coarse aggregate. The influence of the size of coarse aggregate on the RPCA is more significant in high strength (low W/B) concretes than in normal strength (high W/B) concretes.
3. With decreasing W/B, the interfacial zone quality of concrete made with crushed gravel improves more significantly than for round gravel concrete, according to their RPCAs.
4. RPCA depends not only on the strength, size, and shape but also on reactivity of the aggregate.

Acknowledgments

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