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The influence of RPCA on the strength and fracture toughness of HPC

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Abstract

The paper presents the study on the relationship among mechanical properties, including compressive strength, splitting tensile strength, fracture toughness, and rupture probability of coarse aggregate (RPCA) of high-performance concrete (HPC) with varied aggregate sizes. For the maximum aggregate size of 16 mm, the compressive and splitting tensile strength and the corresponding RPCA reached the maximum values. As the mechanical properties linearly increased with the increasing RPCA, RPCA has been confirmed as a useful parameter to express the mechanical behavior of HPC. Preliminary analysis also showed good relationships between the mechanical properties and RPCA.

Keywords: RPCA; Mechanical properties; Fracture toughness; High-performance concrete

1. Introduction

Concrete as a composite material consists of hardened cement paste, aggregate, and interface. From the viewpoint of composite, the strength is mainly determined by the properties of the weakest phase in the composite. Many investigations confirmed that normal-weight aggregate is the strongest phase in low- or middle-strength concrete. Failure always happens inside hardened cement paste and/or along the interface. However, for high-strength concrete mixture with normal aggregate, say compressive strength greater than 40 MPa, or lightweight concrete, many researchers showed that cracks usually passed through the aggregate and observed the higher proportion of rupture of coarse aggregate with the naked eye [1–4]. In addition, Zaitsev and Wittmann [5] numerically modeled the cracking process assuming that cracks originated at the hardened cement paste–aggregate interface. Their results showed that the cracks went around the aggregate particles for normal-strength concrete. For lightweight and high-strength concrete, some cracks could pass through the aggregate straightly. The transformation of the failure mode could lead to the change of the mechanical properties of concrete [6,7]. In order to quantitatively describe the rupture proportion of coarse aggregate and investigate its influence on the mechanical properties of concrete, we have proposed the rupture probability of coarse aggregate (RPCA) and investigated the influence of water–binder (W/B) ratio, maximum aggregate size, and aggregate type on the RPCA [8]. On the fracture surface of concrete, the ratio of the area of ruptured coarse aggregates to the total projected area of coarse aggregates is defined as the RPCA. In this study, eight concrete mixes with different sizes of limestone coarse aggregate and different W/B ratios are prepared. The compressive strength, splitting tensile strength, fracture toughness (K_{Ic}), and RPCA of concrete are determined. Thus, the relationships of strength and fracture toughness with RPCA can be established.

2. Experimental procedure

2.1. Concrete mixes and specimens

The cement of ASTM Type I with a 28-day compressive strength of 63.5 MPa and the ultrafine slag powder with a Blaine fineness of 600 m^2/g were used. The crushed limestone coarse with four different sizes (5–10, 10–16, and 16–20 mm single sizes and 5–16 mm grading) were used. The crushed index of aggregate was 8.3%, which is the ratio of crushed aggregate weight under certain pressure to total aggregate weight. Three mixes with different W/B ratios

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Table 1
Concrete mix design

Mix series	W/B	Aggregate size (mm)	Cement (kg/m^3)	Slag (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)
H–44–5–10	0.44	5–10	267	115	740	1110
H–44–10–16	0.44	10–16	267	115	740	1110
H–44–16–20	0.44	16–20	267	115	740	1110
H–26–5–10	0.26	5–10	472	202	632	948
H–26–10–16	0.26	10–16	472	202	632	948
H–26–16–20	0.26	16–20	472	202	632	948
H–30–5–16	0.30	5–16	420	180	657	986
H–26–5–16	0.26	5–16	472	202	632	948

were designed as 0.44, 0.30, and 0.26, respectively. Sulphonated naphthalene formaldehyde was used as the superplasticizer in this study. The concrete mixes are listed in Table 1, where H–X–Y–Z represents the mix proportions, X is the W/B ratio, Y is the minimum aggregate size, and Z represents the maximum aggregate size.

Six $100 \times 100 \times 100$-mm cubes and three $515 \times 100 \times 100$-mm beams were prepared for each concrete mix. All specimens were demoulded 1 day after casting and stored in standard curing room for 27 days. A notch of 50 mm was cut in the center of each beam using a diamond saw at the 28th day. The cube specimens were used for testing the compressive strength and splitting tensile strength. The notched beams were used for determining the fracture toughness (K_{Ic}). The fracture surface was specially treated after the splitting test for determining the RPCA.

2.2. Test procedure

The compressive strength and splitting tensile strength were obtained with the conventional testing machine. The three-point bending tests were conducted on the notched beams in an Instron 8501 servo machine under closed-loop position control. The corresponding maximum load (P_{max}) was used to calculate the midspan bending moment. The critical stress intensity factor (fracture toughness, K_{Ic}) is then calculated using Eq. (1) [9]:

$$K_{Ic} = 6Y(a/W)M_{max}\sqrt{a}/(BW^2) \quad (1)$$

where $Y(a/W)$ is a geometric factor [$Y(a/W) = 1.93 - 3.07(a/W) + 14.53(a/W)^2 - 25.11(a/W)^3 + 25.8(a/W)^4$], $M_{max} = M_1 + M_2$, where M_1 is the bending moment due to the maximum applied load and M_2 is the bending moment due to the self-weight of the beam, B is the breath of the beam, W is the depth of the beam, and a is the notched depth.

The RPCA (Eq. (2)), as postmortem evidence, is defined as

$$RPCA = \frac{\mathrm{RCAA}}{\mathrm{TCAA}} \quad (2)$$

where RCAA is the area of ruptured coarse aggregate and TCAA is the total projected area of coarse aggregates. More details for measuring the RPCA is present in Ref. [8].

3. Experimental results and discussion

The test data of f_c, f_{st}, K_{Ic}, and RPCA are listed in Table 2. As shown in Fig. 1, for the same W/B ratio, both f_c and RPCA increased with the maximum aggregate size (D_{max}) until D_{max} reached 16 mm and thereafter decreased. Similar trends can also be found for f_{st} and K_{Ic}. For the aggregate size 10–16 mm, all f_c, f_{st}, K_{Ic}, and RPCA reached the maximum values regardless of the W/B ratio. Because RPCA followed the same trend as f_c, f_{st}, and K_{Ic}, RPCA can be related to the strength and other mechanical properties of concrete.

We can now replot these results in Figs. 2–4, i.e., f_c, f_{st}, and K_{Ic} vs. RPCA. Almost the same trend of f_c, f_{st}, and K_{Ic} with RPCA can be found. As the W/B ratio decreased, the three mechanical properties f_c, f_{st}, and K_{Ic} and RPCA all increased simultaneously. This is because both the matrix strength and interfacial bonding strength increase with the decreasing W/B ratio. Therefore, the proportion of ruptured coarse aggregate would be increased as expected.

Table 2
Material properties of concrete

Mix series	Compressive strength, f_c (MPa)	Splitting tensile strength, f_{st} (MPa)	Fracture toughness, K_{Ic} (MPa m$^{1/2}$)	RPCA (%)
H–44–5–10	60.3	5.12	0.876	58.4
H–44–10–16	68.1	5.34	0.967	59.5
H–44–16–20	59.1	4.19	0.829	50.8
H–26–5–10	81.7	6.88	1.087	64.6
H–26–10–16	84.6	7.47	1.165	79.9
H–26–16–20	75.7	6.34	1.225	69.7
H–30–5–16	67.5	6.16	1.094	66.4
H–26–5–16	79.8	7.63	1.151	75.9

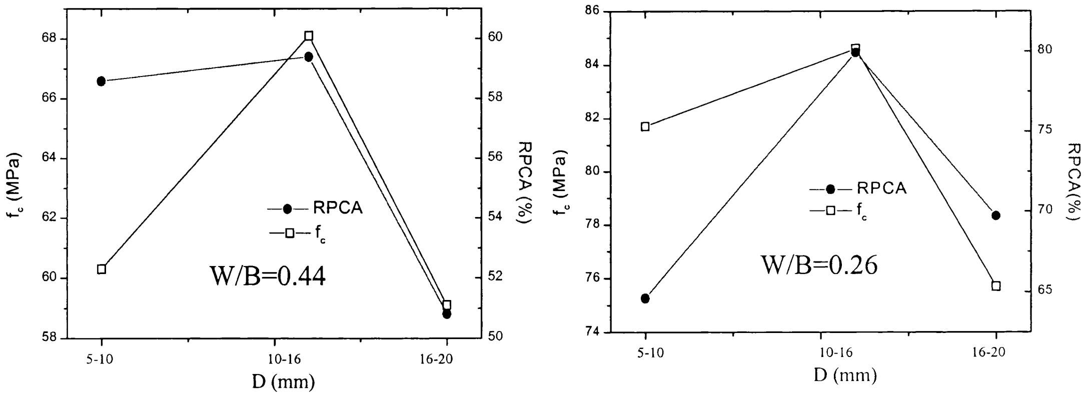

Fig. 1. Relationships of compressive strength and RPCA with aggregate size for different W/B ratios.

For coarse aggregate of single-size 10–16 mm, the f_c, f_{st}, and K_{Ic} of concrete reached the maximum values. Similar research confirmed that the maximum strength and fracture toughness corresponded to an optimum coarse aggregate size for a given type of aggregate and mix [10–12]. In this work, the parameter RPCA also reaches maximum value for coarse aggregate of single-size 10–16 cm. The relationship between RPCA and aggregate size can be explained preliminary. In the range of small particle sizes, 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 large particle sizes, 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.

Figs. 2–4 show that the RPCA can be linearly related to f_c, f_{st}, and K_{Ic} (Eq. (3)):

$$f_{st} = -1.67 + 11.9\text{RPCA} \qquad (r = .943)$$

$$f_c = 14.3 + 88.1\text{RPCA} \qquad (r = .862)$$

$$K_{Ic} = 0.182 + 1.32\text{RPCA} \qquad (r = .881) \tag{3}$$

where r is the linear correlation coefficient. In classical fracture mechanics, the critical stress intensity factor is used to characterize the toughness of materials at fracture. The larger the value of K_{Ic}, the higher crack resistance of materials.

Larrand proposed an empirical relationship between the compressive strength of concrete and the matrix strength as follows [13]:

$$f_{cc} = \frac{af_{cm}}{bf_{cm} + 1} \tag{4}$$

where f_{cc} is the composite strength, f_{cm} is the matrix strength, and a and b are empirical constants depending on the type of aggregate. When the matrix strength is very high, the composite strength tends to be a/b. This means that this ratio is controlled by the intrinsic strength of the rock. On the other hand, for a low matrix strength, Larrand simplified Eq. (4) to obtain Eq. (5):

$$f_{cc} = af_{cm}. \tag{5}$$

As to the strength of concrete, it is thought to be proportional to that of hardened cement paste and interfacial bond [13–15]. For higher-strength concrete, from the analysis above, the coarse aggregate strength will become a part of concrete strength. In this way, we consider the

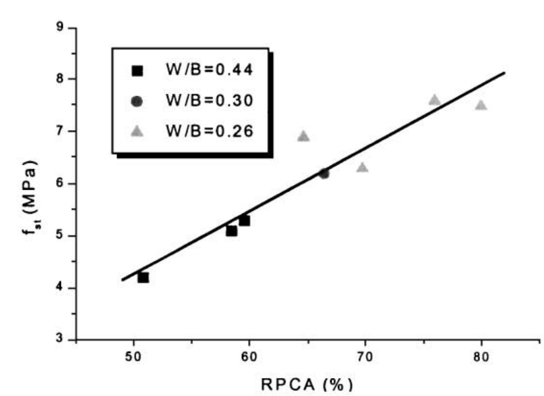

Fig. 2. Relationship between splitting tensile strength and RPCA.

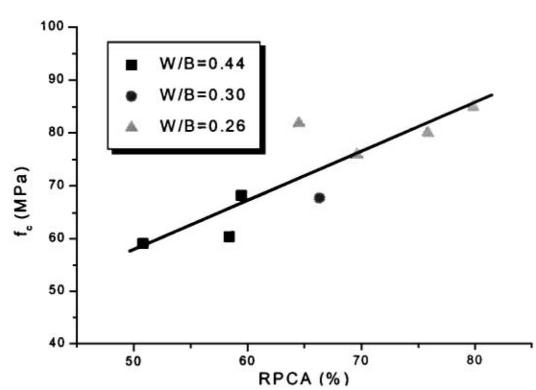

Fig. 3. Relationship between compressive strength and RPCA.

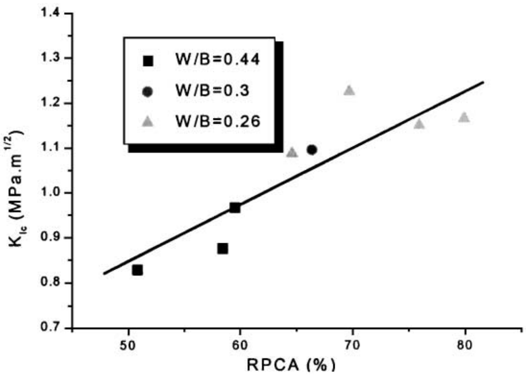

Fig. 4. Relationship between fracture toughness and RPCA.

strength of aggregate contributes to that of concrete, then the strength of concrete can be expressed as:

$$f_c = \alpha f_m(1-V_a) + \beta f_a \mathrm{RPCA} V_a + g f_i (1-\mathrm{RPCA}) V_a$$
$$= [\alpha f_m + (\gamma f_i - \alpha f_m) V_a] + (\beta f_a - \gamma f_i) V_a \mathrm{RPCA} \quad (6)$$

where V_a is the volume proportion of coarse aggregate, f_m, f_a, and f_i are the matrix strength, coarse aggregate strength, and interfacial strength, respectively, and α, β, and γ are the strength coefficients for different phases. According to Refs. [16,17], the bonding strength between mortar and coarse aggregate is proportional to the tensile strength of mortar, thus Eq. (6) could be simplified to obtain Eq. (7):

$$f_c = (\alpha + k\gamma V_a - \alpha V_a) f_m + (\beta f_a - k\gamma f_m) V_a \mathrm{RPCA}$$
$$= K_1 f_m + K_2 \mathrm{RPCA} \quad (7)$$

where $K_1 = \alpha + k\gamma V_a - \alpha V_a$, $K_1 = (\beta f_a - k\gamma f_m) V_a$, and $k = f_i/f_m$. For higher strength matrix, all of coarse aggregates are ruptured and the value of RPCA becomes 1, so the part of strength contributed by coarse aggregates will be expressed as $\beta f_a V_a$. On the other hand, for lower matrix strength, the strength of concrete is equal to the strength of matrix, i.e., $K_1 f_m$. The parameter RPCA can indeed be regarded as an intrinsic parameter that characterizes the strength of composite determined by both matrix and aggregate within the reasonable range of matrix strength.

The simple linear relationship between RPCA and mechanical parameters mentioned above can provide a satisfactory trend of the test data, which indicates that the RPCA of fracture surface is an important influential factor to better understand the mechanical behavior of concrete. Within the range of concrete strength with the same coarse aggregate in the study, RPCA, as the post mortem parameter, can be used to express the mechanical properties of concrete.

4. Conclusions

In this study, fracture surface has been characterized by a new parameter called RPCA. A series of tests were conducted to study the relationship between mechanical properties, including compressive strength, splitting tensile strength, fracture toughness, and RPCA. The following conclusions can be drawn:

1. The RPCA can be regarded as an intrinsic parameter that characterizes the strength of concrete determined by both the properties of matrix and aggregate.
2. The maximum values of compressive strength and splitting tensile strength are obtained corresponding to the maximum aggregate size of 16 mm. The RPCA also reaches its maximum value corresponding to the same aggregate size.
3. All three mechanical properties, compressive strength, splitting tensile strength, and fracture toughness, linearly increase with the increasing RPCA and are well correlated to RPCA.

Acknowledgments

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