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Evaluation method for cracking resistant behavior of reactive powder concrete

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ABSTRACT

Using a shrinkage-restrained ring device with a clapboard, the effect of steel fiber content, sand-binder ratio and water-binder ratio on the cracking resistant behavior of reactive powder concrete (RPC) was investigated by an orthogonal experiment. The study results reveal that steel fiber content has the most significant effect on the cracking resistant behavior of RPC. Cracking ages and cracking coefficients can be used to evaluate the cracking resistant behavior of RPC. The earlier crack age means the poorer cracking resistant behavior of RPC, and the higher cracking coefficient denotes the poorer cracking resistant behavior of RPC. A linear sorting method can be used to approximately reflect the cracking resistant behavior of RPC.

1. Introduction

Reactive powder concrete (RPC) is a relatively new type of ultra-high strength concrete first successfully produced in France [1]. It offers many advantages over normal strength or even some high performance concretes in terms of mechanical and durability properties. It is mainly composed of gradation crushed quartz (excluding the coarse aggregate), cement, quartz powder (or river sand powder), silica fume, superplasticizer, and steel fiber, and measures, such as pressure, heat-treating, are applied in the process of RPC setting [2]. Its application, in a wide variety of fields, such as bridge engineering and military engineering et al. has been increasing and developing [2–7].

The mechanical properties and durability of RPC have been investigated by many scholars [8–12]. Cracking of RPC under constraints impairs the durability of RPC structures and increase the repair cost of RPC. The restrained shrinkage is the basic reason for the cracking of cementitious materials. In another word, the cracking occurs when the tensile stress caused by drying and autogenous shrinkages restrained by external or internal constraints in RPC exceeds its threshold value (namely the tensile strength of RPC). The relationship between the tensile stress and crack opening of RPC was proposed by Fujikake et al. [13], and fracture properties and fracture mechanics of RPC were also studied [14–15]. However, data about cracking of RPC are still scarce, and more studies are needed on the cracking behavior and its evaluation method of RPC under internal and external constraints.

The purpose of this paper is to investigate the relationship between the mix proportion of RPC and the cracking resistant behavior of RPC. In this study, a self-made shrinkage-restrained ring device with a clapboard was used, and the effect of steel fiber content, sand-binder ratio and water-binder ratio on the cracking behavior of RPC was investigated by an orthogonal experiment, and an evaluation method for cracking resistant behavior of reactive powder concrete was proposed.

2. Experiment investigation

2.1. Raw materials

The RPC used in this study was prepared from the following components: Grade 52.5 (Chinese cement grading system) Liangshi Portland cement made in Fujian Province, China; silica fume made in Xining Ferroalloys' Factory with its SiO_2 content of more than 90%, and its particle size of 0.1–0.2 μm; fly ash made in Ningde Datang Power Factory with average particle size of 0.6 μm. The natural Ming River sand was adopted with its maximum grain size of 0.63 mm. The superplasticizer, with the water-reducing ratio of 40% was produced by Sangyuan Company in Fuzhou, China. The steel fibers, with a characteristic length of 13 mm and a characteristic diameter of 0.175 mm, were manufactured by Ganzhou Steel Fiber Company in Jiangxi Province, China.

2.2. Mix proportions of RPC

Three factors, considered in this study, are sand-binder ratio (S/B) (by weight), water-binder ratio (W/B) (by weight), and steel fiber volume in one cubic meter RPC (V_{STF}), where binder B represents the mixture of cement, fly ash and silica fume, namely $B = m_C + m_F + m_{SF}$; $S/B = m_S/(m_C + m_F + m_{SF})$; $W/B = m_W/(m_C + m_F + m_{SF})$; m_C,

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Table 1
Factors and levels in an orthogonal array testing.

Factors		S/B (A)	m_W/B (B)	V_{STF} (%) (C)
Levels	1	0.9	0.16	0
	2	1.0	0.18	2
	3	1.1	0.20	3
	4	1.2	0.22	4

m_F, m_{SF}, m_S, m_W represent the weight of cement, fly ash, silica fume, sand, water in one cubic meter RPC, respectively. Each factor was designed to have four levels in order to better analyze the influence of the three factors on the cracking resistant behavior of RPC. An orthogonal array table of $L^{16}(4^3)$ was designed as shown in Table 1. The weight ratio in the mixture among silica fume (m_{SF}), fly ash (m_F), cement (m_C), and superplasticizer (m_R) is set to be constant, namely m_{SF}:m_F:m_C:m_R = 0.3:0.1:0.9:0.025. The mix proportions of RPC calculated according to Table 1 and the weight ratio in the mixture above are shown in Table 2, where m_{STF}, m_R represent the weight of steel fiber, superplasticizer in one cubic meter RPC, respectively; $m_{STF} = V_{STF}/\rho_{STF}$; ρ_{STF} is the apparent density of steel fibers.

3. Cracking resistant test

3.1. Test method

A self-made shrinkage-restrained ring device including interior steel ring, exterior steel ring, base plate and a clapboard was used. The clapboard introduced was used to increase the circumferential tensile stress by reducing the RPC ring cracking section at the position of the clapboard, and create a stress concentration and therefore shorten the concrete cracking process. All of the RPC ring specimens in the devices had an inner diameter of 315 mm and outer diameter of 395 mm. The wall thickness and height of the interior steel ring were 12 mm and 100 mm, respectively as shown in Fig. 1.

RPC mixtures were poured into the device with 1/2 height of the ring specimens, and the RPC mixture was kept vibrating on a shaking table till the RPC mixture was slightly compacted. Then, the clapboard was fixed by hand, and the rest of RPC mixtures were poured into the ring device. The RPC mixture was vibrated till the cement slurry appeared on the surface of RPC mixture. Finally, a smooth surface of RPC ring specimens was obtained by a steel trowel. The RPC ring specimens were stored in a chamber with the temperature of 20 °C, and the humidity of 65%.

The external steel ring was removed 1 day after pouring. Top and bottom surfaces of the RPC ring specimens were sealed with wax. All the circumferential surfaces of RPC ring specimens were exposed to the above-mentioned environment to allow the moisture in RPC to evaporate only from those surfaces.

Each interior steel ring used in the study had four stain gages attached at the mid-height of the inner surface of the interior steel ring. The strain data were gathered at 20 min intervals via a computer. The self-made shrinkage-restrained ring device for testing the cracking behavior of RPC was shown in Figs. 1 and 2 [16].

Three small specimens with the dimension of 40 mm × 40 mm × 160 mm were cast for the 7 days compressive strengths of each RPC mixture and were vibrated for 4 min on a shaking table and were cured in the same condition as the RPC ring specimens.

3.2. Test results

The 7-day compressive strengths ($f_{cu,7}$) of RPC were tested according to the Chinese Code GB/T 17671-1999 [17]. The group of (1), (6), (11), (16) without steel fibers and the group of (2), (5), (12), (15) with 2% steel fibers cracked in 7 days. Their cracking ages t are listed in Table 3. However, the group of (3), (8), (9), (14) with 3% steel fibers and the group of (4), (7), (10), (13) with 4% steel fibers did not crack in 7 days, and their average strains of the four strain gages attached at interior steel rings $\varepsilon_{st,7}$ can be acquired and shown in Table 3.

4. Analysis and discussions

4.1. Effect of steel fiber content on the crack resistant behavior of RPC

The steel ring circumferential tensile stresses ($\sigma_{\theta c,7}$) at the age of 7 days is calculated by Eq. (1) based on the interior steel ring average strains ($\varepsilon_{st,7}$) at the age of 7 days [18].

$$\sigma_{\theta c,7} = \varepsilon_{st,7} E_{st} h_{st}/h_c \quad (1)$$

where h_c, h_{st} are the thicknesses of the RPC ring specimens and internal steel ring, namely 40 mm and 12 mm, respectively; E_{st} is the interior steel ring elastic modulus, equal to 1.95×10^5 MPa.

The RPC tensile strength ($f_{t,7}$) at the age of 7 days can be calculated by Eq. (2) from RPC compressive strength ($f_{cu,7}$) at the age of 7 days, which can be obtained by fitting the test data available in the reference [19] based on the regressive analysis.

$$f_{t,7} = 0.46 f_{cu,7}^{0.75} \quad (2)$$

The earlier crack age means the poorer cracking resistant behavior of RPC. If the PRC does not crack in 7 days, the cracking resistant behavior of the RPC is then evaluated by the cracking coefficient ($F_{t,7}$) which is the ratio of the circumferential tensile stress of RPC ($\sigma_{\theta c,7}$) to its tensile strength at the age of 7 days

Table 2
RPC mix proportions in an orthogonal experiment.

No.	S/B	m_W/B	V_{STF} (%)	m_c (kg/m^3)	m_{SF} (kg/m^3)	m_F (kg/m^3)	m_S (kg/m^3)	m_{STF} (kg/m^3)	m_W (kg/m^3)	m_R (kg/m^3)
(1)	0.9	0.16	0	790	263.1	87.6	1026.7	0	182.5	19.7
(2)	0.9	0.18	2	756.9	252.1	84.1	983.7	156	196.7	8.9
(3)	0.9	0.20	3	732.8	244.0	81.3	952.4	234	211.6	18.3
(4)	0.9	0.22	4	709.8	236.4	78.8	922.5	312	225.5	17.7
(5)	1.0	0.16	2	741.7	247.0	82.3	1071.0	156	171.4	18.5
(6)	1.0	0.18	0	740.7	246.6	82.2	1069.5	0	192.5	18.5
(7)	1.0	0.20	4	696.1	231.8	77.3	1005.2	312	201.0	17.4
(8)	1.0	0.22	3	689.0	229.4	76.5	944.9	234	218.9	17.2
(9)	1.1	0.16	3	704.6	234.6	78.2	1119.2	234	162.8	17.6
(10)	1.1	0.18	4	683.0	227.4	75.8	1084.9	312	177.5	17.1
(11)	1.1	0.20	0	697.1	232.1	77.4	1107.3	0	201.3	17.4
(12)	1.1	0.22	2	669.7	223.0	74.3	1063.7	156	212.7	16.7
(13)	1.2	0.16	4	670.3	223.2	74.4	1161.5	312	154.9	16.8
(14)	1.2	0.18	3	663.9	221.1	73.7	1150.4	234	172.6	16.6
(15)	1.2	0.20	2	657.8	219.0	73.0	1139.8	156	190.0	16.4
(16)	1.2	0.22	0	658.4	219.3	73.1	1140.9	0	209.2	16.5