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Analysis of fracture process zone of concrete based on extended finite element method and virtual crack model

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Abstract. To research binding characteristics of rebar in reactive powder concrete components, this paper has analyzed influence of various factors on binding characteristics by adopting beam-type test method and has established binding stress-slipping constitutive model and has proved after comparing with common C40 concrete that: integration principle of binding stress-slipping curve of reactive powder concrete test sample and C40 concrete test sample is the same and compressive strength of binding strength of reactive powder concrete are both far more larger than common concrete; where, limiting binding strength is nearly 3 times of C40 concrete, with corresponding slipping value nearly 2 times and corresponding binding strength nearly 1.6 times; binding mechanism between reactive powder concrete and rebar shall be analyzed according to test curve and test sample destruction process. Finally, fire resistance of rebar and reactive powder concrete shall be rested and analyzed.

Key words. Rebar, Reactive powder, Binding, Compressive strength, Mechanics experiments
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1. Introduction

Reactive powder concrete (RPC in brief) is a kind of cement-based composites with good performance, such as super-strength, toughness and duration, etc. At present, a lot of tests and researches have been implemented for materials, mix proportion, curing, duration and strength, etc. of RPC at home and abroad.

Xie Youjun, et al. can formulate reactive powder concrete with compressive strength reaching 200MPa by mixing ultra-fine coal ash and by hydrothermal curing. Literature [3] has researched RPC duration, which is 70 times of common C30

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concrete after research; Literature [4] has initially put forward calculation method for mix proportion of reactive powder concrete, which is also applied in relevant foreign pilot project; Literature [7] has established anticrack calculation model of reactive powder concrete beam based on test and research and has put forward right section anticrack calculation formula with sectional influence coefficients of resistance moment 1.65 (rectangular section) and 1.90 (T-shape section); Literature [8] has put forward calculation formula for right section bearing capacity of rebar RPC beam based on bending test of 3 rebar RPC beams and calculation of stress graph in sectional compressive area is equivalent to that of rectangular stress graph by referring to common concrete method and stress resultant of reactive powder concrete in tensile area can be obtained by test value repeatedly; Literature [9] has established calculation formula of right-section bearing capacity of reactive powder concrete beam by finite element model and concrete stress in compressive area is similar to triangular distribution and value of sectional tensile area RPC resultant force and reinforcement ratio.

RPC has better mechanical performance, excellent durability and volume stability and is construction materials with excellent performance, which has been applied to bridge, house, tunnel, sea and renovation and reinforcement, etc. There are many domestic researches in RPC formulation technology, material performance and component design, while there are few actual engineering cases. To promote application of RPC to project, the author summarizes and discusses research progress of RPC at home and abroad in recent years and introduces formulation principle and technology and concludes RPC and mechanics performance of component. Because RPC does not include aggregate, there is no mutual occlusion function between coarse aggregate in both sides of skew split, so that test value of shear-carrying capacity of RPC sloping beam section is lower than predicted value [05}}}. In consideration of sea work, chemical workshop and salt lake area work on durability of construction materials and this paper also introduces durability of RPC, such as resistance to chloride ion penetration, carbonation resistance, freezing and thawing performance and corrosion resistance, etc. In consideration of fire risk of sea work and buildings in salt lake area, RPC thermostable performance and preventive high-temperature explosion measures are introduced. Finally, extensive application prospect shall be displayed by introduction to RPC pilot work.

This paper has analyzed influence of various factors on binding performance by adopting beam-type test method and has established binding stress-slipping constitutive model has been established and compares it with common C40 concrete and binding mechanism between reactive powder concrete and rebar shall be analyzed according to test curve and test sample destruction process to research binding characteristics of rebar in reactive powder concrete component. Finally, fire resistance of rebar and reactive powder concrete shall be rested and analyzed.

2. Test general

2.1. Test material and performance

Adopt HRB500 high-strength rebar produced by Hebei Steel Group and rebar diameter and strength are listed in Table 1. Steel fiber is HRH extra fine steel fiber produced by Hongruilai (Beijing) Science & Technology Co., Ltd., with diameter 0.22mm and length 13mm and tensile strength is larger than 2800MPa.

Table 1. Actually measured strength table of rebar

Diameter (mm)	Rebar yield strength (MPa)	Rebar limit strength (MPa)
6	600.9	753.4
8	588.1	736.1
10	576.3	738.9
16	566.8	682.0
18	589.6	712.0

To research influence principle of RPC strength on binding performance of rebar, RPC is divided into three kinds according to strength, represented by numbers: H1, H2 and H3 and each RPC mix proportion is listed in Table 2 and steel fiber volume mix rate of H1 RPC is 1.5% or 2%.

Table 2. Mix proportion of reactive powder concrete

ROC number	Cement (%)	Slag (%)	Steel fiber (%)	Sand (%)	Water to binder ratio	Admixture (%)
H1	24.0	24.0	2	43.0	0.17	2.4
H2	28.8	19.2	2	42.3	0.17	2.4
H3	32.2	15.8	3	42.2	0.16	2.4

Curing method and time of test sample of test strength are the same and compressive strength test sample is cube with edge length 70mm and test sample of splitting strength is cube with edge length 150mm and actual measured values of strength are listed in Table 3.

Table 3. Mechanical performance of RPC

Number	Compressive strength (MPa)				Splitting strength (MPa)			
	1Test block 1	2Test block 2	3Test block 3	Mean value/MPa	1Test block 1	2Test block 2	3Test block 3	Mean value/MPa
H1	135.6	132.4	137.8	135.3	17.6	17.8	20.0	18.5
H2	146.9	152.7	141.6	147.1	18.1	19.3	21.0	19.8
H3	170.5	172.8	168.7	170.7	19.7	22.1	22.4	21.4

2.2. Test sample

In table 4, H1∼H3 represent RPC kinds and test sample numbers in table 4 are divided into two kinds according to different test purposes. ① Test group that researches rebar embedment length influence principle: letter after the 1st "-" represents test sample form (L represents standard cube with edge length and Z represents center drawing) and number after the 2nd "-" represents rebar diameter and number after the 3rd "-" represents rebar embedment length. H1-LZ-10-30 test sample is the first kind of RPC, central pull-off test of cube with rebar diameter 10mm and embedment length 30mm. ② Test group of thickness influence principle of protective layer: NZ represents for central pull-off test sample of prism, BZ for plate-type central pull-off test sample, LP for cubic eccentric pull-off test and number after the 2nd "-" represents rebar diameter and number after the 3rd "-" represents thickness of protective layer. H2-HZ-16-32 test sample represents the second kind of RPC, central pull-off test sample of prism with rebar diameter 16mm, thickness of protective layer 32mm and dimension 80mm×80mm×150mm; H2-BZ-8-6 is the second RPC, plate-type central pull-off test sample with rebar diameter 8mm, protective layer 6mm and dimension 150mm×150mm×20mm; number H3-LP-8-10 is the third kind of RPC, cubic eccentric pull-off test sample with rebar diameter 8mm and thickness of protective layer 10mm in eccentric direction.

2.3. Test method

All test samples shall be molded in one time, of which casting face shall be parallel to rebar axis and rebar level shall be placed in formwork and rebar shall be isolated from RPC within certain length with plastic sleeve within certain length on both ends of formwork to prevent loading terminal RPC of test sample from being squeezed locally. Cover preservative film for test sample after vibrating for 1 minute in vibration table and remove formwork after curing for 2d in curing room with constant temperature and humidity, curing for 1d in constant temperature and 3d steam curing, with temperature 60oC in the 1st day and 90 oC in later 2 days. Displacement sensor is fixed in rebar freedom end and relative slipping volume of rebar and RPC shall be measured. Load with 1000kN hydraulic multi-functional tester and adopt system measurement data for DH3815N static force data.

See table 4 for all test samples number and specific parameters of all test samples. Test sample number B in table is abbreviation of beam test (Beam test) and subsequent numbers are: binding length-thickness of protective layer-steel fiber volume. BC40 is C40 concrete test sample. Binding length of C40 concrete test sample is 80mm and thickness of protective layer is 20mm and there is no stirrup in test sample and carbon fiber sheets shall be bond to shearing stress area to assist shearing. See Literature [10∼11] for specific dimension and test process of reactive power concrete test sample.

Table 4. Parameters for beam-type test sample

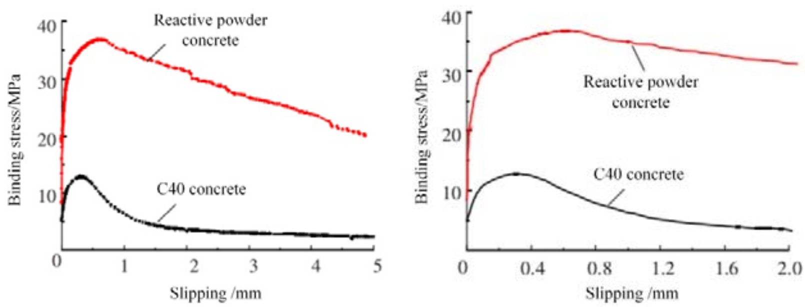
Concrete types	Test sample number	$Vt/1\%$	Thickness of protective layer/mm	Binding length/mm
Reactive powder concrete	B50-20-0.0	0.0	20	50
	B50-20-0.5	0.5	20	50
	B50-20-1.0	1.0	20	50
	B50-20-1.5	1.5	20	50
	B50-20-2.0	2.0	20	50
	B50-15-2.0	2.0	15	50
	B50-25-2.0	2.0	25	50
	B64-20-2.0	2.0	20	64
	B64-25-2.0	2.0	25	64
	B64-30-2.0	2.0	30	64
	B80-20-2.0	2.0	20	80
	B80-25-2.0	2.0	25	80
	B80-30-2.0	2.0	30	80
C40 concrete	BC40	0.0	20	80

3. Result analysis

3.1. Binding performance comparison of different concrete substrates

In this test, parameters of B80-20-20 group reactive powder concrete test sample are the same with C40 concrete test sample and comparison and analysis on its binding stress-slipping curve and binding strength shall be implemented by combining with test result.

Fig.1 is comparison figure for binding stress-slipping curve of B80-20-20 group reactive powder concrete test sample are the same with C40 concrete test sample in this test.



(a) Binding stress—whole slipping curve (b) Partial enlarged drawing

Fig. 1. Relation curve of different concrete binding stress-slipping

It can be seen from Fig.1 that integral principles of binding stress-slipping curve between two kinds of concretes and deformed rebar are similar, while there is a little difference in curve characteristics in all stages. Free end slipping of C40 concrete is earlier than reactive powder concrete and free end starts to slip when binding strength of C40 concrete test sample is 5MPa; free end starts to slip when binding strength of reactive powder concrete test sample is 10MPa; after free end slips, binding stress of reactive powder concrete test sample increases in relatively fast speed; Slope of ascent stage of curve is relatively large, while binding stress of C40 concrete is relatively slow; when binding stress of reactive powder concrete test sample is 33MPa and binding stress of C40 concrete test sample is 11MPa, curve begins to present non-linear characteristics and non-linear section of reactive powder concrete test sample is relatively long and its curve is more moderate than C40 concrete test sample curve; after binding stress decreases, binding stress of C40 concrete test sample decreases in relatively fast speed and curve slope is relatively large and there is relatively long residual section, while decrease section of reactive powder concrete test sample is relatively moderate and it still decreases and there is no residual section when slipping value reaches 5mm.

3.2. RPC strength class division

Include data in Literature [7,13,16-19] to corresponding classes according to compressive strength of RPC cube with edge length 70.7mm and calculate average value and variation coefficient of compressive strength of RPC cube with edge length 70.7mm of each class edge length. See Fig. 2 for relation between average value and variation coefficient of compressive strength of RPC cube with edge length 70.7mm.

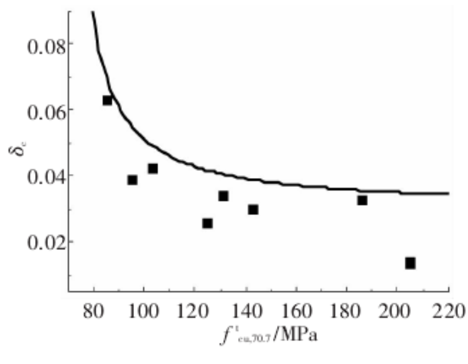


Fig. 2. Average value and variation coefficient of compressive strength of RPC cube

Comprehensive strength of RPC cube is divided into 12 classes: 90∼100 MPa, 100∼110 MPa , … , 200∼210 MPa according to 10 MPa for one class. It can be seen from Fig. 2 that variation coefficient of compressive strength of RPC cube will reduce with improvement of strength because the higher RPC compressive strength is, the higher the uniformity will be. For safety, top covering line of data points is taken as function of compressive strength variation coefficient of RPC cube with edge length 70.7m, of which formula is:

$$\delta_c = \frac{2}{3f_{cu,70.7} - 205} + 0.03\,. \tag{1}$$

Discreteness of RPC mechanical performance is influenced by several independent factors, such as microstructure, defective dimension, component and homogeneity, etc., Where there is no independent factor that plays decisive role, so, it is assumed that compressive strength of RPC cube with edge length 70.7m complies with normal distribution. To coordinate with current specification in China, standard value of compressive strength of RPC cube with edge length 70.7m can be calculated according to formula (2):

$$f_{cu,k,70.7} = f_{cu,70.7} - 1.645\sigma = (1 - 1.645\sigma)\, f_{cu,70.7}\,. \tag{2}$$

Combining formula (1) and (2), average value of compressive strength and variation coefficient of RPC cube with edge length 70.7m corresponding to different RPC strength classes can be obtained and see table 5 for calculation results.

Table 5. RPC strength class and performance index

Strength class	/MPa Standard value for compressive strength/MPa	Average value for compressive strength/MPa	Variation coefficient
RPC90	90	99	0.0517
RPC100	100	109	0.0464
RPC110	110	119	0.0432
RPC120	120	129	0.0410
RPC130	130	140	0.0393
RPC140	140	150	0.0382
RPC150	150	160	0.0373
RPC160	160	171	0.0365
RPC170	170	181	0.0359
RPC180	180	192	0.0354
RPC190	190	202	0.0350
RPC200	200	213	0.0346
RPC210	210	223	0.0343

3.3. Statistical regression of anchoring characteristics value

See table 6 for test result of all beam-type test samples, where test data of B80-30-2.0 test sample are not obtained because rebar is not snapped.

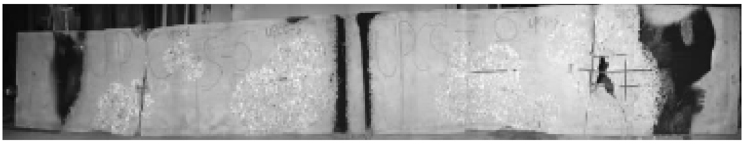
Table 6. Test result of beam-type test sample

Test sample number	τ_0/MPa	τ_s/MPa	τ_u/MPa	s_s/mm	s_u/mm	Destruction form
B50-20-0.0	8.01	28.80	28.80	0.0801	0.0801	S
B50-20-0.5	8.81	29.49	32.05	0.0462	0.3274	S+P
B50-20-1.0	8.98	33.32	39.56	0.1744	0.7251	S+P
B50-20-1.5	9.10	34.34	41.41	0.1238	0.8601	S+P
B50-20-2.0	8.69	32.85	45.68	0.1220	0.9838	P
B50-15-2.0	8.73	30.86	41.70	0.1592	1.0330	S+P
B50-25-2.0	8.30	35.07	47.35	0.1062	1.0956	P
B64-20-2.0	9.51	34.38	41.28	0.1442	0.8257	S+P
B80-20-2.0	10.37	33.01	36.82	0.1459	0.6419	S+P
B64-25-2.0	9.37	35.28	43.93	0.1173	0.8450	S+P
B80-25-2.0	10.14	33.74	38.81	0.1183	0.6603	S+P
B80-30-2.0	—	—	—	—	—	B
BC40	5.33	10.31	12.83	0.0810	0.3007	S+P

It can be seen from Table 4 that compressive strength, steel fiber volume, thickness of protective layer and binding length of rebar of reactive powder concrete will exert influence on binding strength and corresponding slipping value; splitting strength, "Ding" (slipping acceleration strength) will increase with increase of thickness of protective layer; limited binding strength, "Ding" will increase with increase of compressive strength, steel fiber volume, thickness of protective layer and binding length of rebar of reactive powder concrete and will decrease with increase of binding length of rebar and will decrease with increase of slipping value and thickness of protective layer and will be greatly influenced by steel fiber volume and binding length of rebar.

3.4. Check calculation for high-temperature explosion and anti-explosion of pre-stressed concrete

During use, there may be compressive stress in pre-compression area of pre-stressed component and tensile stress level is relatively low even if pre-compression area is subjected to tension under use load and certain compressive stress and relatively small tensile stress leads to that crack hardly occurs on counter-firing face of beam plate under use load, so that it is difficult for inner steam to escape under fire disaster and relatively high steam pressure is caused and therefore, inner tensile stress of concrete caused by steam can reach tensile strength of concrete to bring about explosion of counter-firing face concrete of pre-stressed component. Zheng Wenzhong, et al. has concluded explosion condition under fire disaster of 38 pre-stressed concrete beam plates and 8 pcs. simply supported one-way slabs of sliding block explodes to different degree and 3 pcs. continuous one-way slabs explode to different degree and test sample explosion is shown in Fig.3. It is found that the higher the pre-stressed level of pre-compression area in counter-firing face is or the lower the tensile stress is and the higher compressive strength and water content are, it is more easy for concrete to explode or explode seriously.



(a) Explosion condition of counter-firing face

(b) Fracture condition during ignition of plate

(c) Condition of concrete explosion and forming holes from unexposed surface

Fig. 3. Concrete explosions for pre-stressed continuous plate under fire

See Fig. 4 for top covering surface of pre-stressed concrete explosion. For pre-stressed plate, concrete explosion of counter-firing face is verified with$\sigma_{ct} \leq 1.36 f_{tk} - 2.3$, where σ_{ct} is lower limit value of tensile stress of counter-firing face concrete under normal temperature (MPa) and is standard value of normal-temperature tensile strength of concrete (MPa).

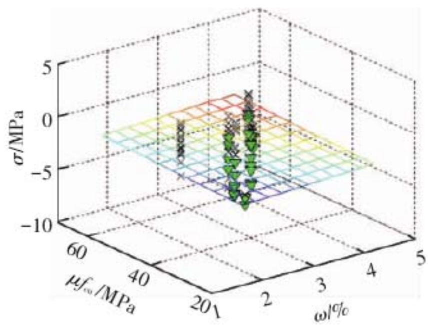


Fig. 4. Top covering face on explosion

4. Conclusion

(1) Rebar embedment length is main factor that influences high-strength rebar and RPC binding performance. When rebar embedment length increases, limit pullout load F and initial slipping load r in free end increase and limit bond stress and peak load slipping volume decrease. Embedment length increases from 3d to 4d and decrease of load accelerates after passing peak and then increases; when embedment increases to 5d and 6d, rebar will be broken.

(2) It is proved by central pull-off test of prism: when thickness of protective layer increases, the number of stripes and width of test sample both decrease and

decrease section of load-slipping curve slows down. Minimal thickness of protective layer is confirmed by cubic eccentric pull-off test and plate-type central pull-off test and it is found: when thickness of protective layer exceeds rebar diameter, binding performance of rebar and RPC can be ensured.

(3) When RPC strength increases, tensile limit load and initial slipping load will increase and decrease of load accelerates after passing peak.

(4) When steel fiber mixing rate increases, decrease section of load-sliding curve slows down.

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