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Research Article

The Effect of Gravel Content on Fluidity and Mechanical Properties of Reactive Powder Concrete

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Abstract

Reactive powder concrete (RPC) is one kind of ultra-high performance concrete (UHPC), which has ultra-high strength, high toughness and high durability. However, its high cost and specific curing regime limit its extensive application. To reduce cost and simplify curing regime, cement-silica fume-fly ash ternary cementitious system, natural medium sand with well gradation for totally replacing the quartz sand and normal curing regime for specimens were used. Then six types of mix proportions for RPC were designed, and the gravel content that replaced natural medium sand were 0%, 20%, 25%, 30%, 35% and 40%, respectively. The fluidity and mechanical properties of the specimens, such as compressive, flexural, and splitting tensile strength, were investigated. Results show that the fluidity always increase with the gravel content and slump-flow is more apparent than that of the slump, while the compressive, flexural, and splitting tensile strength increase until reach the peak value when the gravel content is about 35%, and these strengths are 20%, 90% and 65% higher than that of RPC without gravel, respectively. Therefore, RPC incorporated with gravel can not only improve its fluidity and mechanical properties, but also reduce the engineering cost. The conclusions obtained in the study are of important theoretical value to direct the similar engineering practice.

Keywords: Reactive powder concrete, Gravel content, Fluidity, Mechanical properties

1. Introduction

Reactive powder concrete (RPC) is one kind of ultra-high performance concrete (UHPC) [1, 2], and with high strength concrete (HSC) and high performance concrete (HPC), this new cement-based composite was developed firstly by Pierre Richard and Marcel Cheyrezy who came from BOUYGUES company in French in 1993, which has ultra-high strength, high toughness and high durability. According to its composition, the applied pressure and heating temperature in curing process, RPC can be divided into RPC200 and RPC800 [3].

RPC is composed of active powder materials such as cement and mineral admixtures, fine aggregates, additives, high-strength steel fibres and/or organic synthetic fibres and water. After homogeneously mixing, it is set and hardened through heat-pressing curing process. The emergence of RPC had attracted extensive attentions relying on its performance advantages in many aspects, and it had been gradually applied in many engineering fields, such as bridge engineering, municipal engineering, building engineering, nuclear power engineering, military engineering, and so on. For example, the single-span pedestrian/bikeway bridge, which had been erected in July 1997 in Sherbrooke, Quebec Province, Canada, is the world's first major structure to be built with RPC [4, 5]. Lafarge company built Mars Hill single-span bridge using RPC in Iowa State, USA, which was described as the The Future Bridge [6]. Nanjing Air Force Design Office in China cooperated with Shanghai Metro Corporation, had studied the application of RPC in air defense works of metro, and formulated the local standard of RPC protection door for air defense works [7].

Although lots of scholars around the world have carried out extensive, systematic and in-depth research on various properties of RPC, its high engineering cost and specific curing regime still limit its extensive application.

2. State of the art

Recently, studies on RPC have been mainly focused on the following aspects: mix proportion, static and dynamic mechanical properties, high temperature residual strength and spalling properties, toughening and fracture properties, hydration dynamics and microstructure, durability.

Han et al. used the short-cut super-fine stainless wire (SSSW) with super-fine diameter and high aspect ratio to reinforce RPC, and the calculation models of flexural strength andtoughness of SSSW RPC were established [8]. Ruan et al. investigated the effects of four types of multi-walled carbon nanotubes (MWCNT) on the mechanical properties of RPC and they found that adding proper type and content of MWCNT could effectively improve mechanical properties of RPC [9]. Yiğiter et al. used class-C fly ash (FA) to replace cement with a high-volume rate up to 60%, and the results showed that compressive strength of 200 MPa could be reached [10]. Liu et al. carried out experimental and numerical studies on impact resistance of RPC targets reinforced with 44-layer steel wire meshes, which indicated an effective impact resistance in comparison with the previous studies on UHPC with additions of fibres

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and basalt aggregates [11]. Yi et al. performed ANFO blast tests on reinforced UHSC and RPC panels, and they found that UHSC and RPC have better blast explosion resistance than normal strength concrete [12]. Ju et al. conducted numerical and experimental study on the thermal spalling mechanism of RPC exposed to high temperature, and they found that the numerical simulation was in good agreement with the experimental observations [13]. Hou et al. studied the effect of fire insulation on fire resistance of hybrid-fibre reinforced RPC beams, the post-fire test observation reveals that no fire-induced spalling occurred [14].

İpek et al. examined the effect of pre-setting pressure on RPC, and the maximum flexural strength of 36.40 MPa and three times toughness of that were obtained under 25 MPa pre-setting pressure, with the volume of sample decreased 7.9% [15]. Bonneau et al. studied the hydration kinetic of RPC by using electrical conductivity and isothermal calorimetry, they obtained a linear relationship between the logarithm of conductivity and the degree of hydration and proposed a continuous determination of the degree of hydration based on electrical conductivity [16]. Tam et al. examined the influences of water-to-binder ratio and super-plasticizer dosage on the drying shrinkage and water permeability of RPC, several recommendations were given to reduce drying shrinkage and water permeability of RPC [17]. Tao et al. investigated the effect of steel fibre content, sand-binder ratio and water-binder ratio on the cracking resistant behaviour of RPC by an orthogonal experiment, and they revealed that steel fibre content has the most significant effect [18]. Peng et al. produced RPC specimens whose content of phosphorous slag powder (PS) and silica fume was about 50% (by the weight of binder), and the freeze-thaw and sulphate resistance tests verified their excellent durability properties [19]. The related researches were also conducted by others [20-22].

Replacing fine aggregate with gravel plays a positive role in reducing engineering cost, however, there are few studies on replacing fine aggregate of RPC with gravel up to now. So the effect of gravel content on fluidity and mechanical properties of RPC were studied in this study.

The rest of this study is organized as follows: Section 3 describes materials and the test design. Section 4 analyzes the results and gives some discussions. Section 5 provides the relevant conclusions.

3. Methodology

3.1 Materials

The cement P.O 42.5 with density of 3.11 g/cm^3 was produced in Jiaozuo Jiangu Cement Co., Ltd, China. The characteristic parameters of fly ash and silicon fume are shown in Tables 1 and 2, respectively. The fine aggregate is natural river sand with fineness modulus of 2.7 and apparent density of 2.6 g/cm^3. The coarse aggregate is gravel with 5-10 mm particle size and continuous gradation, and the mud content is less than 0.5% after washing. The form of steel fibres are shearing end profiled, with diameter of 0.22 mm and length of 13 mm. The water reduction rate of polycarboxylate super-plasticizer is 30%. Defoamer is DF-849 type white powder and mixing water is tap water.

Table 1. The characteristic parameters of fly ash

Item	Value
Density (g/cm^3)	2.88
Bulk density (g/cm^3)	1.25
Specific surface area (cm^2/g)	2100
SO_3 (%)	1.20
CaO (%)	3.60
Loss of ignition (%)	1.02

Table 2. The characteristic parameters of silicon fume

Item	Value
Density (g/cm^3)	1.65
Bulk density (g/cm^3)	0.69
Average particle size (μm)	0.15
Specific surface area (cm^2/g)	28
SiO_2 (%)	≥ 98
Al_2O_3 (%)	≤ 0.70
Fe_3O_4 (%)	≤ 0.60
MgO (%)	≤ 0.50
CaO (%)	≤ 0.20

3.2 Experimental program

3.2.1 Mix proportions

As shown in Table 3, according to the theory of maximum compactness and the principle of minimum water requirement, six types of mix proportions were designed and denoted as S_1, S_2, S_3, S_4, S_5, and S_6, respectively, in which the gravel 5-10 mm content replaced natural medium sand were 0%, 20%, 25%, 30%, 35% and 40%, respectively.

Table 3. The mix proportions of RPC

Specimen No.	Amount (kg/m^3)								
	Cement	Fly ash	Silicon fume	Medium sand	Gravel	Water	Super-plasticizer	Defoamer	Steel fibre
S_1	895	268	90	895	0	250	15	3.759	156
S_2				716	179				
S_3				671	224				
S_4				627	268				
S_5				582	313				
S_6				537	358				

Note: The content of super-plasticizer was 1.2% of the cementitious materials and that of defoamer was 0.3% by mass, while that of steel fibre was 2% of those by volume.

Table 4. The test items and the requirements for specimens

Test items	Amount (Group)	Size (mm × mm × mm)
Compressive strength	9	100 × 100 × 100
Flexure strength	3	100 × 100 × 400
Splitting tensile strength	3	100 × 100 × 100

Note：The compressive strength was tested for 7 days, 14 days and 28 days, respectively.

3.2.2 Specimens preparation

The test requirements for specimens are shown in Table 4. The specimens were produced by uniaxial forced mixer and the procedure was as follows: (1) To place natural medium sand, gravel and steel fibres into the mixer, and it were mixed for 2 minutes. (2) To place cement, fly ash and silicon fume into the mixer, and it were mixed for 2 minutes. (3) To place water (with super-plasticizer and defoamer dissolved in) slowly into the mixer , and it was mixed for 5 minutes.

The casting of specimens and the measurement of the rheological properties of the RPC were commenced as soon as mixing being completed. All the specimens were placed on a vibrating table and remained for 1 minute after filling, and then were moved to the standard curing room with its exposed surface being covered in plastic sheeting to prevent moisture evaporation. The specimens were demoulded after casting for 48 hours, and then sprinkled water on the specimens every morning until 28 days.

3.2.3 Test program

The fluidity of the RPC which included slump and slump-flow were tested according to reactive powder concrete in China (GB/T 31387-2015), as shown in Fig. 1.

The compressive strength were tested by electronic hydraulic testing machine with a 1000 kN capacity at a loading rate of 1.20-1.40 MPa/s according to reactive powder concrete in China (GB/T 31387-2015), the compressive strength setup was shown in Fig. 2.

The splitting tensile strength were tested by the electronic hydraulic testing machine at a loading rate of 0.08-0.10 MPa/s according to standard for test method of mechanical prosperities on ordinary concrete in China (GB/T 50081-2002), the splitting tensile strength test was shown in Fig. 3.

The flexural strength were tested by universal testing machine with a 100 kN capacity at a loading rate of 0.08-0.10 MPa/s according to GB/T 31387-2015 in China. Four-point bending was used in the test and the distance between the two supports was divided into three equal parts by the two loading points, the flexural strength setup was shown in Fig. 4.

Fig. 1. Slump and slump-flow

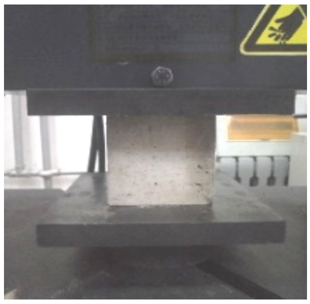

Fig. 2. Compressive strength test

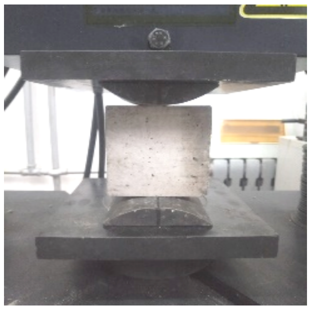

Fig. 3. Splitting tensile strength test

Fig. 4. Flexural strength setup

4. Results and Discussion

The tests results were listed in Table 5.

Table. 5. The test results

specimen	Fluidity (mm)		Compressive strength (MPa)			Flexure strength (MPa)	Split tensile strength (MPa)
	Slump	Slump-flow	7d	14d	28d		
S_1	220	400	74.2	82.8	97.7	8.26	9.08
S_2	240	440	75.3	83.3	96.1	12.37	11.75
S_3	250	510	78.8	86.5	102.6	13.54	14.53
S_4	260	550	79.7	86.2	107.6	14.36	14.44
S_5	290	580	82.7	92.1	116.5	15.71	15.02
S_6	330	650	73.6	81.4	104.8	10.78	12.59

4.1 Fluidity of fresh RPC

Fig. 5 showed the change trends of fluidity of fresh RPC with the gravel content increasing, it could be seen that the fluidity always increased with the gravel content and slump-flow, which was more apparent than that of the slump. When the gravel content exceeded 35%, the segregation of RPC occurred, the reasons could be explained as follows: firstly, the binder played a lubricant and roll-bead role in aggregates. Secondly, the total specific surface area decreased with the increase of the gravel content because of the gravel content was small than that of sand. Thus, considering the two reasons mentioned above, there would be redundant binder to cover the surface of the aggregates, which could cause the segregation of fresh RPC. Therefore, a reasonable sand rate was one of the key factors determining the properties of RPC.

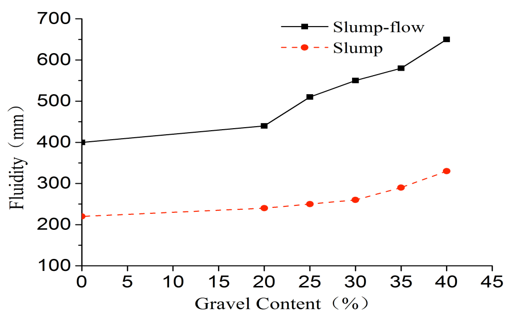

Fig. 5. Fluidity of fresh RPC

4.2 Compressive strength of RPC

Fig. 6 showed the change trends of compressive strength of RPC with the gravel content increasing, we found that the compressive strength of RPC increased at first and then decreased, and it reached the peak value when the gravel content was about 35%, the strength was 11% and 20% higher than that of RPC without gravel at 7 days and 28 days, respectively.

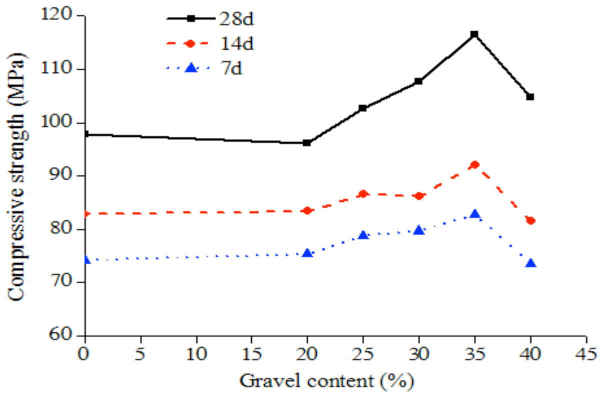

Fig. 6. Compressive strength of RPC

The incorporation of gravel played a skeleton role in RPC which can enhance its compressive strength. However, as mentioned above in 4.1 part, when the gravel content exceeded 35%, there would be redundant binder to cover the surface of the aggregates, which could cause the segregation of fresh RPC and decreased compressive strength of RPC. Hence, considering the interaction of the two reasons mentioned above, the optimum gravel content was about 35% for the compressive strength of RPC.

4.3 Flexural strength of RPC

Fig. 7 illustrated the relationship between the flexural strength of RPC and the gravel content, we found that the flexural strength of RPC increased roughly linearly at first and then decreased, and it reached its peak value when the gravel content was about 35%, which was 90% higher than that of RPC without gravel.

As mentioned above in 4.2 part, it was effected by the interaction of the segregation of fresh RPC and the skeleton role in RPC, the optimum gravel content was about 35% for the flexural strength of RPC. Through the linear fitting, the relationship expression for the roughly linear growth part with the gravel content of RPC showed as follows, $y = 0.21x + 8.22$, whose correlation coefficient R^2 was 0.95.

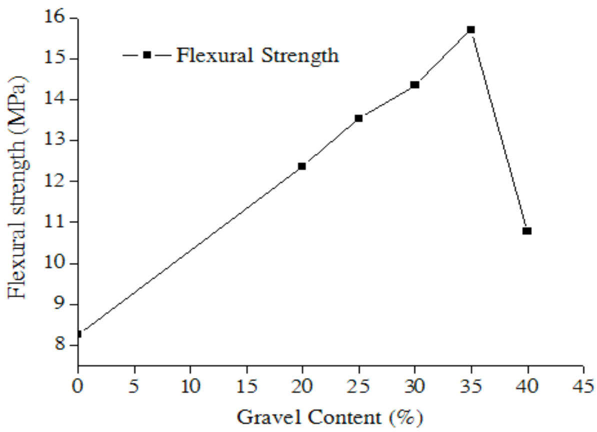

Fig. 7. Flexural strength of RPC

4.4 Splitting tensile strength of RPC

Fig. 8 illustrated the relationship between the splitting tensile strength of RPC and the gravel content, we found that the flexural strength of RPC increased approximately at first and then decreased, and it reached its peak value when the gravel content was about 35%, which was 65% higher than that of RPC without gravel.

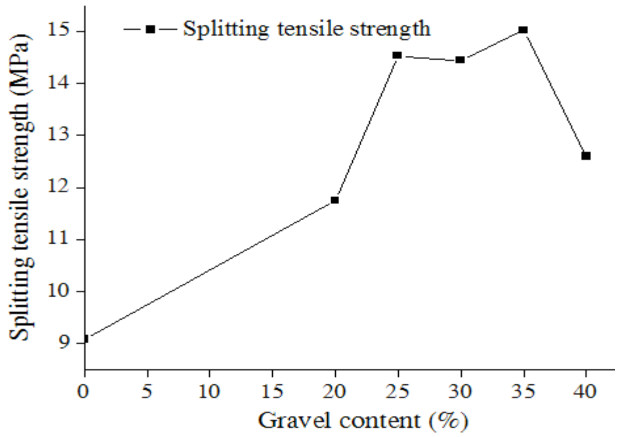

Fig. 8. Splitting tensile strength of RPC

As mentioned above in 4.2 part, it was effected by the interaction of the segregation of fresh RPC and the skeleton role in RPC, the optimum gravel content was 35% for the splitting tensile strength of RPC.

5. Conclusions

To study the effect of gravel content on fluidity and mechanical properties of reactive powder concrete, some mechanical tests of RPC specimens were conducted, the following conclusions were obtained:

(1) The fluidity always increased with the gravel content and slump-flow was more apparent than that of the slum. When the gravel content exceeded 35%, the segregation of RPC occurred. Therefore, a reasonable sand rate was one of the key factors determining the properties of RPC.

(2) The mechanical properties of the specimens, such as compressive, flexural, and splitting tensile strength increased until the peak values when the gravel content was about 35%, the strengths were 20%, 90% and 65% higher than that of RPC without gravel, respectively.

(3) Through the linear fitting, the relationship expression for the roughly linear growth part with the gravel content of flexural strength of RPC showed as follows, $y = 0.21x + 8.22$, whose correlation coefficient R^2 was 0.95.

RPC incorporated with gravel can not only improve its fluidity and mechanical properties, but also reduce the engineering cost. The research results can provide references for the similar engineering practice.

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