Study on the Influence of Mix Proportion on the Mechanical Properties of Reactive Powder Concrete

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ABSTRACT. Reactive Powder Concrete (RPC), as a cement-based composite material with high strength, good ductility, excellent durability, and favorable volumetric stability, exhibits promising applications in modern engineering construction. Investigating the influence of concrete mix proportions on the mechanical properties of RPC is crucial for enhancing its overall performance. This study investigates the influence of individual factors, including water-cement ratio, silica fume content, sand-cement ratio, and volume fraction of steel fibers, through single-factor experiments on the mechanical properties of RPC. The results demonstrate that reducing the water-cement ratio, controlling the amount of silica fume and sand-cement ratio, and increasing the volume of steel fibers all contribute to the improved flexural and compressive strength of RPC specimens.

Keywords: Reactive Powder Concrete; Mix proportion; Mechanical Properties

1 Introduction

With the increasing spans of architectural structures, taller buildings, and diverse applications in harsh and specialized fields, higher performance expectations are imposed on concrete. Reactive Powder Concrete (RPC), produced through the method of “highly compact cementitious matrix”, eliminates coarse aggregates in concrete. By employing the principle of dense packing and utilizing quartz sand with a maximum particle size of 400 μm as aggregate, RPC exhibits remarkable characteristics such as high strength, good ductility, excellent durability, and favorable volumetric stability. Consequently, it has become one of the focal points in current concrete material research [1-3].

RPC primarily consists of water, cement, well-graded quartz sand, fine powders (typically including mineral admixtures such as slag powder, fly ash, and silica fume), high-efficiency water-reducing agents, and steel fibers. The production of RPC involves a process of compression and heating during molding and curing [4-6]. By eliminating coarse aggregates, RPC reduces defects at the interface between aggregates and matrix, thereby enhancing the interfacial bonding and increasing the matrix strength [7]. The addition of mineral powders improves the compactness of the matrix,

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leading to enhanced strength and durability [8]. Furthermore, the incorporation of steel fibers enhances the ductility of RPC, significantly increasing its tensile and flexural strength and improving its toughness [9].

The fundamental mix proportions of RPC in this study were initially established based on literature data. Subsequently, single-factor experiments were carried out to investigate the influence of mix proportions on the mechanical properties of RPC, including the water-cement ratio, composition of cementitious materials, sand-cement ratio, and volume of steel fibers.

2 Experiment

2.1 Materials

Cement is one of the most crucial raw materials in RPC. This study employed P.O 42.5 ordinary Portland cement, which was produced by a cement company in Shanxi. Its chemical composition and key physical properties are presented in Table 1 and Table 2, respectively.

Table 1. Chemical composition of P.O 42.5 ordinary Portland cement

Chemical Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss
Proportion /%	22.12	4.58	2.91	63.01	2.87	2.21	2.85

Table 2. Physical and mechanical performance indicators of cement

Specific Surface Area (SSA)	Stability	Setting Time		Compressive Strength			Flexural Strength		
		Initial Setting	Final Setting	3d	7d	28d	3d	7d	28d
348	Qualified	168	248	24.5	36.2	49.7	5.5	7.8	10.3

Silica fume is a by-product of ferrosilicon industrial smelting and one of the most commonly used active components in Reactive Powder Concrete (RPC). Due to its high reactivity and particle-filling effect, it plays a crucial role in ensuring the strength of RPC. In this study, silica fume produced by Xian Lin Yuan micro-silica fume Co., Ltd. was selected. The silica fume appeared as a grayish-white powder with an average particle size of 0.1-0.15 μm and a specific surface area of 15-27 m^2/g. Its bulk density ranged from 150 to 200 kg/m^3. Table 3 illustrates the detailed chemical composition.

Table 3. Chemical composition of silica fume

Chemical Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O
Proportion /%	95.3	1.2	1.0	0.4	0.6	1.5

Fine quartz powder is a commonly used component in RPC. The selected fine quartz powder for this study had an average particle size of approximately 10 μm and a SiO_2 content of over 99%.

Quartz sand, as a fine aggregate, can be used in the preparation of RPC. Both quartz sand and natural sand are suitable for RPC formulation. However, quartz sand is preferred due to its high hardness, excellent interface properties, and incomparable characteristics to natural sand in terms of particle grading, average particle size, and texture. Therefore, quartz sand is often chosen for RPC preparation. In this study, refined quartz sand with an average particle size of 200-425 μm and a SiO_2 content exceeding 99.6% was selected.

The addition of steel fibers in RPC was primarily aimed at enhancing the concrete's inherent brittleness and acting as a crack-inhibiting, reinforcing and toughening agent within the matrix. In this study, short-cut steel fibers with a nominal diameter of 0.22 mm and a length of 13 mm were selected, exhibiting a tensile strength of 2800 Mpa.

As RPC typically employs an extremely low water-cement ratio (typically ≤0.20), the addition of an appropriate proportion of superplasticizer becomes crucial to ensure ease of molding and achieve high compactness in the mixture. In this study, a Polycarboxylate superplasticizer produced by a concrete admixture manufacturer in Shandong was selected, which demonstrated a water reduction rate exceeding 30% and exhibited no slump loss within half an hour.

2.2 Experimental scheme

RPC has an extremely low water-cement ratio, resulting in poor flowability and high viscosity of the mixture. Therefore, a well-designed mixing and forming process is a crucial factor in ensuring that RPC specimens exhibit good workability and hardening performance. Since RPC eliminates coarse aggregates in its composition, making the system more similar to cement mortar, a planetary mortar mixer was chosen as the mixing device. Additionally, taking inspiration from the slurry coating and stone mixing process used in conventional concrete and considering the results of practical experiments, the process was improved and optimized. The specific implementation steps are as follows:

(1) Material Weighing: We weighed various materials according to the designed mix proportion;

(2) Mixing: We added cement and silica fume to the mixing drum, slowly stirred them for 3 minutes, and then mixed the pre-measured mixing water with the superplasticizer uniformly. After adding approximately 70% of the water with the superplasticizer and stirring them slowly for 1 minute, we added the remaining 30% of the water with the superplasticizer and stirred them rapidly for 2 to 4 minutes. After obtaining a well-flowing slurry, we added the fine quartz powder and stirred rapidly for 2 minutes. Subsequently, we added the quartz sand, stirring rapidly for 3 minutes. Finally, we gradually added the steel fibers (if required) and stirred them until they were uniformly dispersed.

(3) Forming: Pouring half of the mixture into the mold and vibrating for 1 minute, we poured the remaining slurry into the mold and vibrate for another 1 minute. After smoothing the surface with a trowel, it was covered with a plastic film.

(4) Demolding and Curing: After 24 hours of static rest in the forming room, we demolded the specimens and conducted curing according to the concrete curing standards.

The determination of the flexural and compressive strength of RPC specimens follows the guidelines specified in GB/T 17671-1999 (Temperature: 20°C±1°C, Relative Humidity: ≥95%), which were performed at the age of 28 days.

3 Results and Discussions

3.1 The effect of water-to-binder ratio on the mechanical properties of RPC

The water-cement ratio is one of the main factors influencing the strength of concrete [10]. According to the Power model, the gel porosity and capillary porosity in hardened cement paste are closely related to the water-cement ratio. Lower porosity results in higher compactness of the matrix, leading to higher concrete strength. Table 4 shows the mix proportions of RPC under different water-cement ratios. The setting of the water-cement ratio includes cement and silica fume as cementitious materials, and the water in the superplasticizer is also considered as part of the mixing water mass.

Table 4. Mix proportions of RPC under different water-cement ratios

Sample	W/C	Cement	SF/C	QP/C	QS/C	WRA/C
1	0.16	1	0.30	0.30	1.1	0.01
2	0.18	1	0.30	0.30	1.1	0.01
3	0.20	1	0.30	0.30	1.1	0.01
4	0.22	1	0.30	0.30	1.1	0.01
5	0.24	1	0.30	0.30	1.1	0.01

During the forming process, the flowability of the slurry gradually deteriorated as the water-cement ratio decreased. When the water-cement ratio was reduced to 0.16, the mixture exhibited higher viscosity and poorer flowability, requiring an appropriate extension of the mixing time. Conversely, when the water-cement ratio exceeded 0.18, the mixture showed better flowability, and the use of a superplasticizer can enhance the workability of the slurry. Therefore, the water-cement ratio should be greater than 0.18. The corresponding test results of flexural and compressive strength for RPC specimens at different ages are plotted in Figure 1. As the water-cement ratio decreased, the flexural and compressive strengths of RPC specimens both exhibited significant improvements, with the compressive strength showing an almost linear increasing trend. It is foreseeable that if the water-cement ratio continues to decrease within the feasible range of formability, the compressive strength of the specimens can further increase. The main reason for this is the high homogeneity of the RPC matrix, where the matrix structure becomes denser as the water-cement ratio decreases, leading to continuous strength improvement. Considering both workability and strength requirements, a water-cement ratio of 0.18 to 0.20 is deemed more appropriate for RPC.

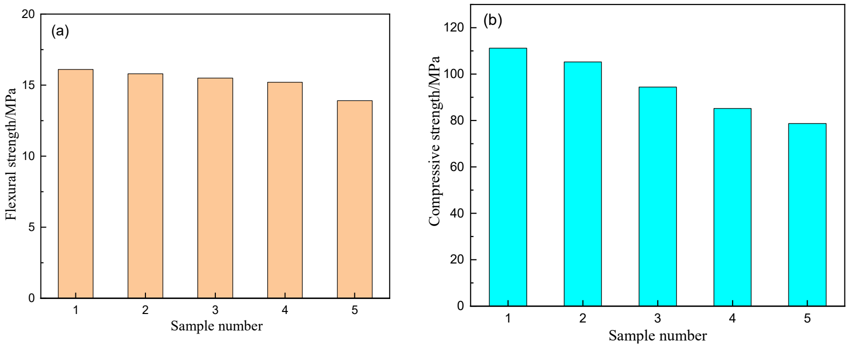

Fig. 1. Flexural strength (a) and compressive strength (b) of RPC at varying water-cement ratios

3.2 The effect of silica fume mixing amount on the mechanical properties of RPC

In order to investigate the isolated influence of silica fume on the mechanical properties of RPC, the relative dosage of silica fume to cement was varied while keeping other mix proportions constant. At the same time, the total amount of silica dioxide in the raw material system (silica fume + fine quartz powder) was maintained unchanged. The specific mix proportions are presented in Table 5.

Table 5. Mix proportions of RPC at different silica fume dosages (wt%)

Sample	W/C	Cement	SF/C	QP/C	QS/C	WRA/C
6	0.20	1	0.15	0.45	1.1	0.01
7	0.20	1	0.20	0.40	1.1	0.01
8	0.20	1	0.25	0.35	1.1	0.01
9	0.20	1	0.30	0.30	1.1	0.01
10	0.20	1	0.35	0.25	1.1	0.01

Although the water-cement ratio of 0.20 was adopted at this stage, there were still significant differences in the workability of the mixtures during the actual forming process at different mix proportions. With an increase in the dosage of silica fume, the workability of the mixture initially improved but then deteriorated. When the silica fume/cement ratio (SF/C) was 0.15, the workability of the mixture was poor. At that point, the total amount of cementitious materials in the system was relatively low, requiring a longer mixing time to fully coat the aggregates with the paste. When $0.2 \leq SF/C \leq 0.3$, the mixture exhibited good workability. However, at SF/C=0.35, the higher dosage of silica fume led to an increase in the viscosity of the paste, resulting in reduced workability and adding difficulty in achieving a smooth surface in specimens during molding.

The corresponding test results of the flexural and compressive strength of RPC specimens at different ages are shown in Figure 2. According to the experimental results, under standard curing conditions at 28 days, the sample 5 specimen exhibited the highest flexural and compressive strength. As the dosage of silica fume increased, the flexural and compressive strengths of the specimens decreased. The flexural strengths of sample 8, 9, and 10 specimens were similar; except for sample 6, the compressive strengths of the other specimens were below 100 MPa, possibly due to the lower reactivity of silica fume under standard curing conditions. From the test results, considering both workability and the overall compressive strength of the specimens, it is more appropriate to set the mass ratio of silica fume to cement in RPC to be between 0.25 and 0.3.

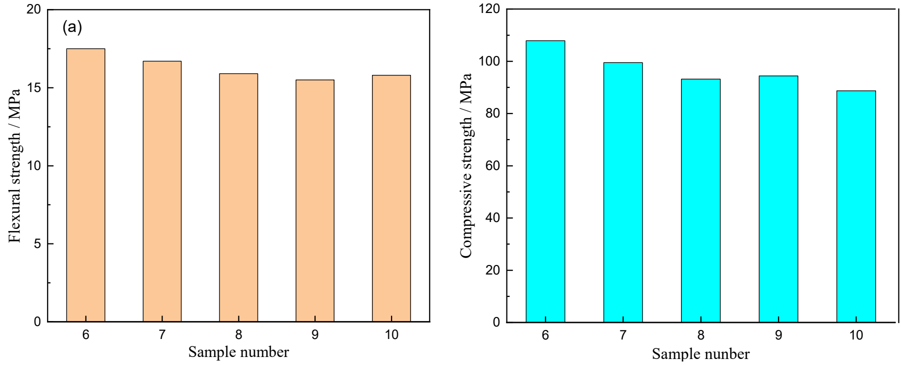

Fig. 2. Flexural strength (a) and compressive strength (b) of RPC at different silica fume dosages

3.3 The effect of sand-cement ratio on the mechanical properties of RPC

The sand-cement ratio refers to the proportion of quartz sand to cement by mass and is also a significant factor influencing the strength and workability of RPC. The mix proportions with single-factor variations in the sand-cement ratio are presented in Table 6. From the forming process perspective, the workability of the mixture gradually decreases with an increase in the sand-cement ratio. When the sand-cement ratio was ≤1.1, the mixture exhibited good workability, and the increase in the sand-cement ratio had minimal impact on workability. However, when the sand-cement ratio reached 1.3 and 1.5, the workability of the mixture significantly decreased. The main reason was that the average thickness of the paste layer on the surface of the aggregates became smaller. As a result, the bonding force between the sand and the paste diminished, leading to a lack of sufficient paste between the aggregates to form a cohesive whole. This adversely affected the workability of the mixture and increased the difficulty in the forming process.

Table 6. The mix proportions of RPC at different sand-cement ratios (wt%)

Sample	W/C	Cement	SF/C	QP/C	QS/C	WRA/C
11	0.20	1	0.30	0.30	0.7	0.01
12	0.20	1	0.30	0.30	0.9	0.01

13	0.20	1	0.30	0.30	1.1	0.01
14	0.20	1	0.30	0.30	1.3	0.01
15	0.20	1	0.30	0.30	1.5	0.01

The test results for the flexural and compressive strength of RPC at different sand-cement ratios are presented in Figure 3. When increasing the sand-cement ratio, the flexural and compressive strength of RPC specimens showed an initial increase, followed by a gradual decrease. When the sand-cement ratio increased from 0.7 to 1.1, there was a slight increase in the compressive strength of the specimens. However, when the sand-cement ratio increased from 1.1 to 1.5, a significant decrease in compressive strength was observed. This decrease can be attributed to the reduced workability of the mixture during forming, which led to an increase in structural defects. Additionally, the thinner paste layer covering the surface of aggregates resulted in a decline in interfacial performance. Considering both workability and strength test results and taking into account the effect of the sand-cement ratio on compressive strength shrinkage, a sand-cement ratio of 1.1 was found to be a reasonable choice for RPC.

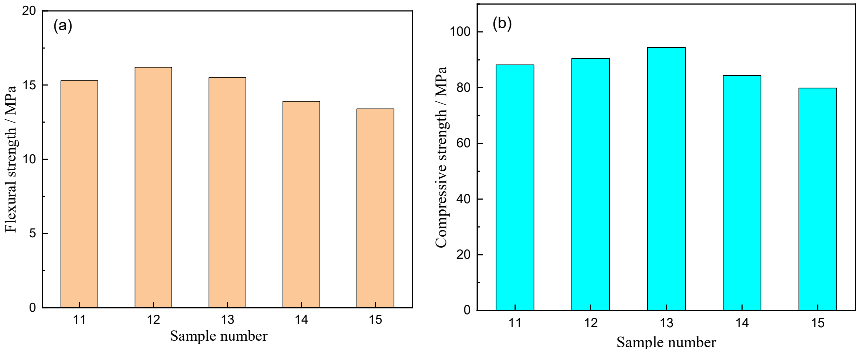

Fig. 3. Flexural strength (a) and compressive strength (b) of RPC at different sand-cement ratios

3.4 The effect of steel fiber volume fraction on the mechanical properties of RPC

Enhancing the inherent brittleness of RPC by incorporating steel fibers is a crucial approach to achieving exceptional mechanical performance in the material [11]. In this study, the effect of varying the volume fraction of steel fibers (while maintaining other ratios based on mass) on the mechanical properties of RPC was investigated. The volume fractions of steel fibers used in the study are presented in Table 7.

Table 7. Mixture proportions of RPC with different volume fractions of steel fibers

Sample	W/C	Cement	SF/C	QP/C	QS/C	Steel fibre	WRA/C
16	0.20	1	0.30	0.30	1.1	0	0.01
17	0.20	1	0.30	0.30	1.1	0.5%	0.01

18	0.20	1	0.30	0.30	1.1	1.0%	0.01
19	0.20	1	0.30	0.30	1.1	2.0%	0.01
20	0.20	1	0.30	0.30	1.1	3.0%	0.01

During the molding process, the workability of the mixture gradually decreased with an increase in the volume fraction of steel fibers. When the volume fraction of steel fibers was relatively high, an excessive amount of steel fibers tended to cluster and interlace between the lumps of the mixture, leading to reduced release of mixing water and a significant decline in the fluidity of the paste. In this case, it was necessary to extend the mixing time adequately to ensure the full release of mixing water and uniform dispersion of steel fibers. Additionally, multiple layers of compaction were required to ensure the compactness of the molded specimens and minimize the occurrence of internal defects.

The corresponding test results of the RPC specimens' flexural and compressive strength were presented in Figure 4. It can be observed that the addition of steel fibers significantly enhanced the flexural and compressive strength of RPC. When 0.5vol% of steel fibers were added to the system, the compressive strength of the specimens exhibited a noticeable improvement compared to the plain RPC control group. As the volume fraction of steel fibers continued to increase, the compressive strength of the specimens also increased. When the volume fraction of steel fibers reached 3.0vol%, the compressive strength of the specimens showed an increase of over 50% compared to plain RPC. However, when the volume fraction of steel fibers was 0.5vol%, the increase in flexural strength was relatively small compared to plain RPC. It was only when the volume fraction of steel fibers exceeded 1 vol% that a significant enhancement in flexural strength was observed.

The above results indicated that, while the addition of steel fibers can effectively improve the strength of RPC specimens, the influences of the volume fraction of steel fibers on the flexural and compressive strength of the specimens differ. For flexural strength, the volume fraction of steel fibers needed to be higher than a certain value to fully exert its reinforcement effect. Considering workability, strength test results, and cost, controlling the volume fraction of steel fibers at around 2 vol% was more appropriate.

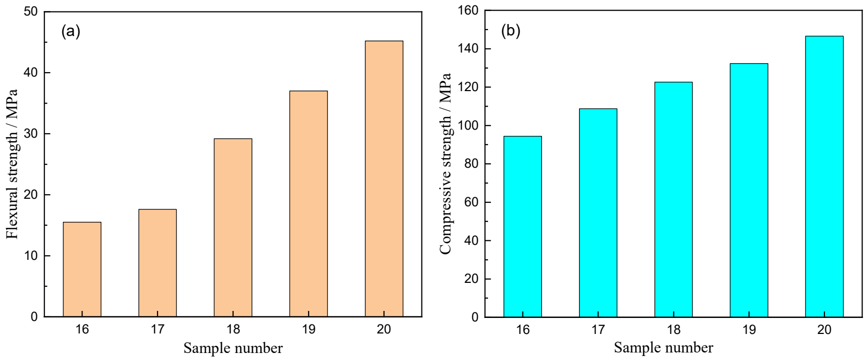

Fig. 4. Flexural strength (a) and compressive strength (b) of RPC with steel fiber added

4 Conclusions

The mix proportion of reactive powder concrete (RPC) is a key factor affecting its mechanical properties. As the water-cement ratio decreases, both the flexural and compressive strength of RPC show significant improvements, with compressive strength exhibiting an almost linear increase. However, with an increase in the amount of silica fume, the flexural and compressive strength of RPC decreases. The trend for RPC's flexural and compressive strength with varying sand-cement ratios is characterized by initial growth followed by a decline. Additionally, as the volume of steel fibers is increased, the flexural and compressive strengths of RPC also increase. Taking into account RPC's workability, mechanical performance, and cost considerations, the optimal mix proportions are determined as follows: the water-cement ratio should be set between 0.18 to 0.20, the mass ratio of silica fume to cement should be between 0.25 to 0.3, and the sand-cement ratio should be approximately 1.1. Furthermore, the volume of steel fibers should be controlled at around 2% by volume.

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