The influence of materials and production process on RPC compressive strength

Congmi Cheng1*, Xiaofen Zhu1, Yuhai Zhuang2, Juan He1

1School of Civil Engineering, Guangzhou University, Guangzhou 510006, P. R. China
2Guangzhou City Construction & Development Co. Ltd. 510085, P. R. China

Abstract. In addition to the water binder ratio, the production process, fiber, silica fume and admixture have a significant impact on the compressive strength of RPC. Several factors such as materials and production process affecting RPC compressive strength were studied by experiments. It exhibits that the reinforcement influence of steel fiber on RPC is affected by the strength of composite matrix. The higher the strength of composite matrix is, the better the effect of fiber reinforcement is. The compressive strength of RPC can be greatly improved by vacuum vibration forming. The water demand and activity of silica fume have significant influence on the compressive strength of RPC.

1. Introduction
Reactive powdery concrete (RPC) is a kind of ultra high performance concrete with high strength, high toughness and high durability. The compact and uniform internal structure makes it have excellent performance. The compressive strength of RPC is between 100-800 MPa, the flexural strength is between 10-40 MPa, and the fracture energy is between 12-40 kJ/m² [1-3]. The rich research results on the composition, production process, structure and performance of RPC paved the way for its wide application in civil, municipal, nuclear power, petroleum, marine and military structures.

The strength and durability of concrete was improved by way of employing steel fibers and the nano mineral admixtures is the philosophy to develop RPC. High cement content, low water-to-binder ratio and no coarse aggregate are the basic methods for producing RPC [4-6]. The ultimate strain of a cementitious composite decreases as its compressive strength increases. Fibers work as bridges over which the internal strains/stresses can be transferred along the composite systems. Therefore, these fibers stop the concentration of pressures and control the propagation of sizable cracks [2]. The absence of coarse aggregates improves the uniformity of RPC, and there is no obvious interface transition zone between matrix and aggregate [7]. High cement content, low water-to-binder ratio and the use of silica fume give RPC a very compact microstructure, and the inherent defects of the composite are greatly reduced. The porosity of RPC is very low, and the pore diameter is concentrated between 2-3nm, so it has ultra high strength [1]. Increasing the curing temperature is the key to improve the strength of RPC. Although the long-term strength will decrease after high temperature curing, high pressure steam curing is considered to be the best way of RPC curing [8]. Compared with normal temperature curing, high temperature steam curing and autoclaved curing can significantly increase the compressive strength of RPC, but its flexural strength and toughness are reduced [9,10].

It is well-known that increasing the compressive strength for a cementitious composite does not involve enhancement of its all properties, especially tensile strength and strains [2]. Concrete compressive strength is not its essential characteristic because it is its durability that it is more important, it must be admitted that these two characteristics are intimately linked to one another. The
overwhelming importance of the compressive strength in the codes and the ease with which it is measured can explain why the increase of the compressive strength of concrete has been, in a certain way, a constant preoccupation [11]. In this paper, the influence of fiber, silica fume, slag, production process and curing conditions on the compressive strength of RPC is discussed.

2. Materials and methods

2.1 Materials
Portland cement, PꞏI 42.5, Shandong Lucheng Cement Co., Ltd. Silica fume from Sichuan, Beijing and Fujian. The water demand ratios are 111, 107 and 120 respectively, and the activity index (7d fast method) is 120, 119 and 109 respectively. Silica fume from Sichuan was used without special explanation. Slag, grade S95, fluidity ratio is 98%, 28d activity index is 101%, Guangdong Shaoang Songshan Co., Ltd. The aggregate is composed of quartz sand and quartz powder. Among them, the grain size of quartz sand is 0.5-1.5mm, accounting for 85% by mass (Figure 1a); the grain size of quartz powder is 0.1-0.2mm, accounting for 15% by mass (Figure 1b).

Copper plated steel fiber, diameter is 0.2mm; length is 13mm, Tangshan, Hebei. Polycarboxylate superplasticizer, liquid, solid content is 50%, BASF. Silicone defoamer, milky white liquid, pH value is 7.2, Guangdong Chaosu Co., Ltd.

2.2 Test methods
Raw materials were weighed according to the mix proportion. Superplasticizer and water should be put together and stirred evenly before standby. Cement, silica fume, and aggregate were poured into a mortar mixer. After mixing for 1 minute, steel fibers were added to continue mixing. After another minute, water with superplasticizer was added. Defoamer was added after mixing for 2 minutes, and continue mixing for 1 minute. The mixture was poured into a test mold to make cube test specimens with side length of 100mm. The specimens were cured in an environment with a temperature of 20°C and a relative humidity above 95% for 24 h, and then the molds were removed and placed in a steam curing box at 90°C for 48 h. The compressive strength test of RPC was carried out in accordance with Standard for Test Methods of Concrete Physical and Mechanical Properties (GB/T 50081-2016). Fluidity test of RPC was carried out in accordance with Test Method for Fluidity of Cement Mortar (GB/T 2419-2005).

3. Effect of steel fiber content on compressive strength of RPC
Cement-based continue to be subjected to micro-cracking due to its inherent low tensile strength. The increase of strength is accompanied by the decrease of toughness, which can be improved by the use of fiber. Many researchers have demonstrated the effectiveness of using fibers to improve the properties of a cementitious composite [12]. The compressive strength of RPC increases with the increase of steel fiber content. However, there are different conclusions about the influence of steel fiber on the compressive strength of RPC. Sun [13] studied the compressive strength of RPC with steel fiber content of 0 and 2% (by volume), and found that the latter had a 25.0% increase in compressive
strength over the former. Abbas\cite{14} and Arabi\cite{15} show that incorporation of fibers in cement-based materials does not affect its compressive strength much.

In order to grasp the influence of steel fiber content on the compressive strength of PRC, two series of RPC with water-to-binder ratio of 0.19 and 0.22 were prepared. RPCs of the same series has the same mix proportion of mortar, and five different contents of steel fibers with 0, 1, 3, 5 and 7% (by mass) were added respectively to each series of RPCs. The mix proportion of the two series is given in Table 1.

**Table 1.** Mix proportion of RPC with different fiber content

| Name     | Cement (kg/m³) | Silica fume (kg/m³) | Aggregate (kg/m³) | Water (kg/m³) | Admixture (kg/m³) | Defoamer (kg/m³) | Steel fiber (kg/m³) |
|----------|----------------|---------------------|-------------------|---------------|-------------------|------------------|---------------------|
| Series I | 850            | 150                 | 1200              | 180           | 20                | 0.1              | 0-154               |
| Series II| 850            | 150                 | 1200              | 210           | 20                | 0.1              | 0-154               |

Figure 2 presents the relationship between the compressive strength and the steel fiber content of RPC with the water-to-binder ratio of 0.19 and 0.22, respectively. Regardless of the water-to-binder ratio, the compressive strength of RPC increases with the increase of the steel fiber content. When the water-to-binder ratio is 0.22, the compressive strength of RPC increases less with the increase of water-to-binder ratio. When the content of steel fiber increases from 0 to 7%, RPC compressive strength increases from 82.5MPa to 88.1MPa, with an increase of only 6.7%. When the water-to-binder ratio decreases to 0.18, the compressive strength of RPC increases from 119.1 MPa to 157.3 MPa, with an increase rate of 32.1%. It shows that when the strength of cement matrix is low, the contribution of steel fiber to RPC compressive strength is poor. As the strength of the cement matrix increases, the contribution of steel fibers to the RPC compressive strength increases significantly.

![Figure 2. The relationship between compressive strength and steel fiber content of RPC](image-url)

The failure in a cementitious composite begins with the formation of micro-cracks that propagate and eventually coalesce to generate macro cracks, which cause fracture if not controlled \cite{16}. The inclusion of fibers prevents the propagation of existing and/or initiated cracks by improving the crack tip plasticity. When the water-to-binder ratio is low, the matrix is dense and high strength, and the adhesion between the fiber and the matrix is very strong. Fibers prohibit and interrupt the mechanisms of crack formation and propagation by acting as stress-transfer bridges. In the process of compression, fiber plays a role in restricting the development of cracks, which is conducive to the improvement of compressive strength.

Fiber has little effect on the initial crack load of cement-based composites \cite{17}. When the water-to-binder ratio is high, there are a lot of pores in the composite, the strength of cement matrix is low, and the initial crack appears at low loads. The weak matrix also has less grip on steel fibers. Therefore, when the RPC is broken, the fiber is pulled out, which weakens the ability of fiber to disperse cracks. Accordingly, the strengthening effect of fiber on compressive strength is weakened. Therefore, considering the compressive strength only, when the matrix strength is low, incorporation of fibers in
RPC does not have economic value. However, this does not mean that there is no need to add fibers in low strength RPC, because the addition of fibers is very important to flexural strength and toughness.

4. Effect of vacuum vibration forming on compressive strength of RPC

Vibration mixing can significantly improve the workability and compressive strength of RPC \cite{18}. Compression forming can improve the compactness and mechanical properties of concrete \cite{19}. The incorporation of defoamer makes the inside of the specimens denser, and also improves the compressive strength of RPC. To compare the effect of defoamer and vacuum vibration forming on the compressive strength of RPC, two mix proportions of defoamer and no defoamer were adopted, and ordinary forming and vacuum vibration forming were adopted. The vacuum vibration forming adopts a small vacuum vibration machine with a vacuum degree of -0.05MPa. Mix proportion and performance of RPC with different forming methods are given in Table 2.

Table 2. Mix proportion and performance of RPC with different forming methods

| Name | Mix proportion (kg/m³) | Compressive strength (MPa) | Dry apparent density (kg/m³) |
|------|------------------------|----------------------------|-----------------------------|
|      | Cement | Silica fume | Aggregate | Water | Admixtur e | Fiber | Defoamer | Forming method | Compressive strength | Dry apparent density |
| V1   | 850    | 150        | 1200      | 180   | 20        | 132   | 0        | Normal         | 136.5              | 2423               |
| V2   | 850    | 150        | 1200      | 180   | 20        | 132   | 0.1      | Normal         | 152.1              | 2451               |
| V3   | 850    | 150        | 1200      | 180   | 20        | 132   | 0        | Vacuum         | 186.3              | 2594               |
| V4   | 850    | 150        | 1200      | 180   | 20        | 132   | 0.1      | Vacuum         | 189.9              | 2602               |

The use of defoamer can increase the compressive strength of RPC. The compressive strength and dry apparent density of ordinary formed RPC without defoamer (V1) were 136.5 MPa and 2433 kg/m³ respectively. The compressive strength and dry apparent density of ordinary formed RPC with defoamer (V2) were 152.1 MPa and 2451 kg/m³ respectively. The compressive strength and dry apparent density increased by 11.4% and 1.2%. A large number of round holes with diameter of about 1 mm can be observed in RPC without defoamer (Figure 3a). After treatment with defoamer, the large pores in the sample decreased (Fig. 3b), and the compressive strength of RPC increased accordingly.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fracture_surface.png}
\caption{Fracture surface of RPC with different forming methods}
\end{figure}

The density and compressive strength of RPC can be greatly increased by vacuum vibration forming. The dry apparent density and compressive strength of vacuum vibration forming RPC (V3)
are 7.1% and 36.5% higher than those of ordinary forming RPC. This is because the internal structure of RPC formed by vacuum vibration is very dense, the number of pores is greatly reduced (Figure 3c), and the compressive strength is greatly increased.

The compressive strength of vacuum vibration forming RPC with defoamer (V4) is only 1.9% higher than that of vacuum vibration forming RPC without defoamer (V3), and the volume density of the two samples is only 0.3%. The apparent density of the two also differs by only 0.3%. In both sections, there are few pores introduced by additives (Fig. 3c, d). It shows that that vacuum vibration forming can significantly reduce the porosity in RPC, thereby significantly improving the compressive strength of the composite. Due to the obvious effect of vacuum vibration forming to reduce bubbles, the presence of defoamer is meaningless.

5. Effect of silica fume on compressive strength of RPC

The inclusion of nano silica fume has been demonstrated to produce high performance cementitious composite and improve their durability. Silica fume not only plays a role of dense filling, but also has a reactivity. The spherical particles act as balls to improve the fluidity of the mixture and the compressive strength and durability of RPC. Three kinds of silica fume were used to produce RPC with the same mix proportion, and their effects on the fluidity and compressive strength of RPC were compared. The characteristics of each silica fume, mix proportion and compressive strength of RPC are given in Table 3.

Table 3. Mix proportion and performance of RPC with different silica fume

| Name | Mix proportion (kg/m³) | Fluidity (mm) | Compressive strength (MPa) | Silica fume Type | Origin | Water demand ratio | Activity index |
|------|----------------------|---------------|---------------------------|-----------------|--------|-------------------|---------------|
| N1   | 850 150 1200 180 20 132 0.1 | 170 152.1     | 150 124.1                 | SF1             | Sichuan | 107               | 119           |
| N2   | 150 124.1            |               |                           | SF2             | Beijing | 113               | 109           |
| N3   | 100 125.2            |               |                           | SF3             | Fujian  | 120               | 120           |

Although the mix proportion and production process are identical, the compressive strength of RPC produced by the three kinds of silica fume is quite different. The activity index of silica fume SF1 is high and the water demand ratio is low. It can be seen from SEM that it has a better spherical shape and good particle dispersibility (Fig. 4a). This RPC mixture has the best fluidity and can be self-levelling. Its compressive strength is significantly higher than the other two. The compressive strength of RPC with silica fume SF1 (N1) is 22.6% higher than that of RPC with silica fume SF3 (N3). The water demand ratio of silica fume SF2 is low. SEM photo shows that the edges of the particles are fuzzy and there is some adhesion (Fig. 4b). Its activity index is low, and the compressive strength of RPC is also low. The activity index of silica fume SF3 is similar to that of silica fume SF1, but the compressive strength of the latter is 21.5% higher than that of the former. This is due to the serious adhesion of silica fume SF3 particles (Fig. 4c), which makes it difficult to disperse uniformly in RPC. Moreover, the water demand ratio of silica fume SF3 is as high as 120, the fluidity of RPC mixture is poor, and the compressive strength of RPC is low. The above analysis shows that the activity and water demand of silica fume have significant influence on the compressive strength of RPC. When the fluidity of RPC mixture cannot be guaranteed, the water demand of silica fume has a greater impact on the compressive strength of PR.
6. Effect of slag on compressive strength of RPC

It is a common practice to use fly ash, slag, metakaolin and other active minerals to replace part of cement in production of ultra-high performance concrete, and to form fine particle grading with silica fume. After long-term curing, the strength of concrete mixed with mineral admixtures such as ground slag and fly ash is significantly improved\(^{5,20}\). The strengthening effect of mineral admixture is closely related to the curing mechanism. High temperature steam curing makes RPC have higher strength and denser microstructure in comparison with ambient temperature curing. High temperature curing accelerates the hydration and activity of RPC. After high temperature curing, the total porosity and average pore size of RPC are greatly reduced, thereby improving the microstructure and compressive strength of RPC.

In order to explore the effect of slag replacing part of cement on RPC compressive strength, two samples were designed. Only 15% silica fume is added into one sample. In the other sample, in addition to adding silica fume, 15% slag (accounting for the amount of cementitious materials) was used to replace part of cement. The 90°C steam curing for 48h and 96h were used respectively. The mix proportion and performance of RPCs are given in Table 4.

Table 4. Mix proportion and performance of RPC with and without slag

| Name | Mix proportion (kg/m³) | Fluidity (mm) | Compressive Strength (48h) (MPa) | Compressive Strength (96h) (MPa) |
|------|-----------------------|--------------|-------------------------------|-------------------------------|
| K1   | 850 150 0 1200 180 20 132 0.1 | 170 | 152.1 | 153.7 |
| K2   | 700 150 150 1200 180 20 132 0.1 | 165 | 106.3 | 131.5 |

Under the condition of 90°C steam curing for 48h, 15% slag was used instead of cement, and the fluidity of RPC mixture decreased slightly. However, the compressive strength of RPC decreased by 30.1%. This is because the slag does not give full play to its activity due to too short curing time.

Enough curing time is necessary. But for RPC without slag, too long curing time is meaningless. When the steam curing time is extended to 96h, the compressive strength of RPC without slag (K1) increases very little, only 1.1%. However, the compressive strength of RPC with slag (K2) increased significantly to 131.5 MPa, an increase of 23.7%. This indicates that it needs longer curing time to make slag contribute to the compressive strength of RPC. Under the condition of 90°C steam curing for 96h, the compressive strength of RPC with slag (K2) is only 14.4% lower than that of RPC without slag (K1). It shows that it is feasible to reduce the cost by adding slag under the condition of steam curing, but it will lose some strength. If slag is used, it is necessary to extend the curing time.

7. Conclusions

The influence of materials and production process on RPC compressive strength was studied, and the following conclusions can be drawn:

1. For high-strength RPC, fiber is an essential component. The strength of cement matrix is low, the contribution of steel fiber to the compressive strength of RPC is small; the strength of cement matrix is high, the contribution of steel fiber to the compressive strength of RPC is large.

2. For high fluidity RPC, defoamer can significantly improve its compressive strength by 11.4%. Vacuum vibration forming can eliminate bubbles inside the RPC mixture and greatly improve the compressive strength of RPC. When the vacuum degree is -0.05 MPa, the compressive strength of RPC increases by 36.5%.

3. The water demand and activity of silica fume have significant effect on the compressive strength of RPC. The activity indexes of two kinds of silica fume are 119 and 120 respectively, and the water demand ratio is 107 and 120 respectively. The compressive strength of RPC produced by the former is 21.5% higher than that of the latter.

4. Although incorporation of slag can reduce the cost of concrete, it will lose part of its strength. If slag is used to replace part of cement, it is necessary to extend the curing time.
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