Properties of Reactive Powder Concrete under Multi-factor Destruction

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Abstract. This paper presents a comprehensive investigation regarding the carbonation, chloride ions penetration and freeze-thaw durability test of Reactive Powder Concretes (RPCs). Experimental results demonstrate that the depth of carbonization deepens in RPCs with the extension of carbonization time, but the internal carbonization reaction gradually weakens. The wetting-drying cycles accelerates chloride ion migration in concrete. Freeze-thaw cycles reduce the mechanical properties of concrete.

1. Introduction

With the development of social economy, people have higher and higher requirements for building facilities [1-3]. Especially with the development of modern buildings, such as temple, large span, lightweight structure and harsh environment, higher requirements are put forward for the mechanical properties and durability of concrete materials. The emergence of reactive powder concrete (RPC) provides a new way to solve these problems.

RPC is a new cement-based material with super high strength, high durability, high toughness and good volume stability, which was developed in the middle of last century after high strength and high-performance concrete [4]. Compared with other high-strength and high-performance concrete, the important characteristic of RPC is to remove coarse aggregate according to the principle of compact accumulation, make its matrix compact, and have high compressive strength and durability [5-6]. The ductility of high strength concrete is improved by adding steel fibers, which greatly improves the flexural strength and obtains good toughness. In practical engineering, the use of reactive powder concrete instead of ordinary concrete or high-strength concrete can not only reduce the size of structural section and reinforcement, improve the durability and safety of the structure, but also design new structures that ordinary concrete and high-strength concrete cannot design [7].

However, with the development of industry, the external environment of buildings has become harsher, leading to the durability of concrete structures gradually highlighted. Durability includes frost resistance [8], corrosion resistance [9], carbonization reaction [10-11], steel bar corrosion [12-13], alkali aggregate reaction [14] and so on [15-16]. Among all durability problems, corrosion of steel bar caused by chloride ion infiltration and concrete carbonization is the most serious one. In this paper, the effects of carbonization reaction, chloride ion erosion and freeze-thaw breakage on the mechanical properties of RPCs are studied.
2. Experiment set up

2.1 Materials
An ordinary type Portland cement P.O 42.5 was used in this study. The chemical composition of cementitious material was given in Table 1, and some physical and mechanical properties of the Portland cement are also shown in Table 2.

Table 1. Chemical composition of cementitious material

| Chemical composition | SiO₂ | Al₂O₃ | CaO | MgO | SO₃ | Fe₂O₃ |
|----------------------|------|-------|-----|-----|-----|-------|
| Content / %          | 22.34| 4.37  | 61.89| 4.46| 2.28| 2.04  |

Table 2. Physical and mechanical properties of the Portland cement

| Fineness / % | 5.8 |
|--------------|-----|
| setting time / min | Initial 160 | Final 350 |
| Flexural Strength / Mpa | 3d 5.22 |
|                          | 28d 8.68 |
| Compressive strength / Mpa | 3d 24.8 |
|                          | 28d 49.8 |

Silica fume (SF) was used as the secondary binder. The undensified amorphous SF containing above 95% SiO₂ was provided, and the specific surface area was 15300 m²/kg. The physical and chemical properties of the SF were provided in Table 3.

Table 3. Chemical composition of SF (%)

| SiO₂      | >95 |
|-----------|-----|
| C         | 0.45|
| Al₂O₃     | 0.74|
| CaO       | 1.12|
| MgO       | 0.75|
| SO₃       | 0.08|
| Fe₂O₃     | 0.45|
| Na₂O      | 0.16|
| K₂O       | 0.23|

Usually, the water/cement ratio was usually replaced by the water/binder ratio (W/B) to adjust the property of RPC. In order to adjust the rheological behavior of RPC, a polycarboxilate type superplasticizer was utilized with different contents.

According to the particle size, quartz sand is divided into two grading, i.e. coarse sand (particle size 0.250-2mm) and fine sand (0-0.25mm). Finally, steel fiber (length 12mm, diameter 0.35mm) was used to enhance the toughness of RPC.
2.2 Preparation of RPCs
According to our previous work [17], obtaining the desired mix design for producing high performance RPCs requires a specially designed mixing procedure as the properties of RPCs greatly depend not only on the order in which the ingredients are added into the mixture but also on the speed and duration of the mixing process [18]. The raw materials have to mix following certain requirements. Firstly, the pre-weighed dry powders (cement, silica fume and quartz sand) were poured into the concrete mixer and stirred for 5 min. And, the pre-weighed superplasticizer and water were poured into mixer and stirred for about 5 min. Lastly, steel fibers were thrown into mixer and stirred for about 10 min. Then, the mixture was injected into the mold and stored for 24 h at room temperature of about 20 °C. After demolded, the specimens were move into standard curing room and cure for 28 days. Then the samples were stored in water (the time in water was 4 days) until the test being carried out.

2.3 Test
The accelerated carbonation test was carried out in a carbonation chamber for a period of 28 days according to the Chinese National Standard GB/T 50082-2009 “Standard for test methods of long-term performance and durability of ordinary concrete”. In order to evaluate the effect of carbonization on alkalinity of concrete, 1% phenolphthalein solution was used to detect the depth of carbonization. The unchanged region is the carbonized region, and the purple-red region is the carbonized region. The specimens were cast separately and had dimensions of 100×100×400 mm² for carbonation test.

The rapid chloride migration (RCM) method was adopted in the current study. The specimens were cast separately and had dimensions of Φ100×100cm². Before the specimens were mounted on the testing device, the two side faces were coated in order to obtain one-dimensional penetration of the chloride ions. The specimens were then exposed to the wetting-drying cycles. In order to obtaining the total and free chloride ions profiles, the potentiometric titration was employed at the freshly split section. For this reason, powder samples first have to be obtained by grinding the material in layers. The thickness of each layer was 1 mm, and 10 successive layers were considered, in order to obtain an accurate chloride ions profile.

In this study, the freeze-thaw test machine meeting the Chinese National Standard GB/T 50082-2009 requirement was used. The specimens were cast separately and had dimensions of 100x110x400 mm³ for quick frost method. The “freeze” process in fast freeze-thaw cycle was reducing the temperature of RPCs from 5 °C to -16 °C; the “thaw” process is raising the temperature from -16 °C to 5 °C, while the temperature of the coolant reduces from 6±2 °C to -18±2 °C in the “freeze” process and is raised from -18 °C to 60°C in the “thaw” process all in about 3 hours.

3. Results and discussion
3.1 Carbonization reaction of RPCs
Figure 1 is the experimental curve of the depth of carbonization of reactive powder concrete at different carbonization time. It can be seen from Figure 1 that with the extension of carbonization time, the carbonization depth of RPCs deepens, and the carbonization rate in the early stage of the experiment is faster than that in the later stage of the experiment. This is mainly due to the lower concentration of CO₂ in the concrete structure than that in the external environment, and the slower diffusion of CO₂ in the concrete at the later stage of the experiment, which gradually weakens the carbonization of concrete.

Based on the principle of carbonization reaction, the main product of carbonization reaction is calcium carbonate. Temperature, relative humidity and CO₂ concentration influence the carbonation depth of RPCs. The increase of temperature, relative humidity and CO₂ concentration can promote the carbonization reaction. This is because the CO₂ transmission coefficient and chemical reaction coefficient may increase with these factors.
3.2 Chloride ion migration of RPCs
Generally, there are four main driving forces of chloride ion migration in concrete: capillary absorption of water under humidity gradient, ion diffusion under concentration gradient, permeation under pressure gradient, and electric migration under potential gradient. Among them, osmosis plays a more significant role only in the case of larger pressure gradient, while electromigration plays a more significant role only in the case of larger potential gradient, which can be neglected in general. The environment of chloride ion under wet and dry cycling is unsaturated concrete. It is influenced by capillary absorption of water and diffusion of chloride ion. The diffusion rate of humidity is much higher than that of chloride ion concentration. Therefore, capillary absorption under humidity gradient is the main mode of chloride ion transport in concrete under dry-wet cycling environment, and ion diffusion under concentration gradient is the auxiliary mode.

Figure 1. Effect of different carbonization time on carbonization depth of RPCs

Since chloride ions that can bind in the form of a complex salt such as calcium monochloroaluminate hydrate cannot initiate corrosion, the water-soluble chloride ions were measured in order to determine the free chloride ions [19]. Figure 2 shows the migration characteristics of free chloride ions in RPCs after different wetting and drying cycles. It can be seen from Figure 2 that the migration depth of chloride ion in RPCs varies with the increasing number of wet-dry cycles, but the migration law of chloride ion is similar under different cycles.

Figure 2. Migration depth of chloride ion in RPCs after different wetting and drying cycles
3.3 Freeze-thaw cycles of RPCs

The microstructure of reactive powder concrete at room temperature is very dense, and that the calcium–silicate–hydrate (CSH) gel resembles a continuous block. Furthermore, reactive powder concrete is more compact and homogeneous than conventional concrete and exhibits low porosity, although small air bubbles were observed which leads to the defect that reactive powder concrete is still damaged by freeze-thaw cycles. The frost heave cracking caused by water freezing in capillary holes seriously reduces the mechanical properties of concrete, such as elastic modulus, compressive strength and tensile strength, which endangers the safety of the structure. Therefore, freeze-thaw resistance is an important index of concrete durability.

Figure 3 shows the relative flexural strength of RPCs after different freeze-thaw cycles. It can be seen from Figure 3 that the relative flexural strength of RPC decreases gradually with the increase of freeze-thaw cycles, which indicates that the mechanical properties of RPC decrease after freeze-thaw cycles, but the mechanical strength of RPC is less affected by freeze-thaw cycles than that of ordinary Portland cement. This is mainly due to the high compactness of RPC and the use of superplasticizer, resulting in the system of water content is much less than ordinary silicate concrete, so the impact of freeze-thaw cycle is relatively small.

![Figure 3. Relative flexural strength of RPCs after different freeze-thaw cycles](image)

4. Conclusion

Experiments on carbonization, chloride ion migration and freeze-thaw cycles of RPCs were carried out. Based on the experimental work in this paper and the discussion about the test results, the following conclusions can be drawn.

(1) The depth of carbonization deepens in RPCs with the extension of carbonization time, but the internal carbonization reaction gradually weakens.

(2) The wetting-drying cycles accelerates chloride ion migration in concrete. The chloride ions migration rate in inside of RPC is lower than that on its surface.

(3) Freeze-thaw cycles reduce the mechanical properties of concrete. After the same freeze-thaw cycles, the durability of RPCs is better than that of ordinary concrete.

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