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The durability of reactive powder concrete: a review

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Abstract: Reactive powder concrete (RPC) is a new cement-based composite material with ultra-high strength, high ductility and good toughness, which has an extensive application prospects. Based on the domestic and foreign research achievements, the durability of reactive powder concrete is integrally discussed from the standpoints of freezing-thawing resistance chloride ion penetration, carbonization, erosion, and abrasion. Under freeze-thaw cycle, the mass loss of RPC is minimal, chloride ion permeability of RPC is almost negligible, active admixtures can improve the sulfate corrosion resistance of RPC significantly. Moreover, RPC has excellent carbonation resistance and abrasion resistance. The mechanisms of the supreme durability of RPC are analysed in detail. The outlook on topical problems and promising research directions in this field is presented.

1. Introduction

Reactive powder concrete (RPC) is a new type of ultra-high strength and ultra-high performance cement-based composites developed by Richard [1-2] of Bouygues Company of France according to the linear packing density model (LPDM) and the compressible packing model (CPM) and fiber reinforced material technology. RPC has the characteristics of high strength, high toughness, high durability, and high volume stability. Dugat et al. [3] carried out the experiment on the mechanical properties of RPC with a cylinder specimen diameter of 70 mm, height of 180 mm and steel fiber content is 146 kg/m^3. The RPC compressive strength varied from 194 to 203 MPa and its elastic modulus ranged from 62 to 66 GPa. Tai [4] investigated the dynamic compression mechanical properties of RPC under different strain rates and reported that the static strength of RPC was significantly higher than that of normal concrete, while the dynamic energy absorption of RPC increased with the steel fiber content and was proportional to the impact energy. Zheng [5] conducted quasi-static tests of RPC beam-column joints, and test results indicated the seismic performance and shear strength of RPC beam-column joints were better than that of reinforced concrete joints. RPC with ultra-high performance has broad application prospects in civil engineering, mining, nuclear power, municipal, marine, and military engineering. The engineering application of RPC is becoming more and more common. For example, the Jean Bouin stadium in France, which was completed in August 2013 and featured a double curved

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surface structure, had the shell consisting of 3600 pieces of precast RPC sheets.

China will be at the peak of its construction in the future for quite some time. The durability of concrete materials determines the durability of reinforced concrete structures. Therefore, it is of great practical significance to study the durability of RPC materials. At present, scholars in China and abroad have carried out extensive research on the durability of RPC materials, including frost resistance, carbonation resistance, chloride ion resistance, sulfate resistance, chemical solution corrosion resistance and wear resistance. From the research on the durability of RPC at home and abroad, this paper makes a comprehensive discussion on the aspects of frost resistance, chloride ion penetration resistance, carbonation resistance, corrosion resistance and wear resistance and so on.

2. Review of the durability of reactive powder concrete

2.1 Freezing-thawing resistance

Using the orthogonal test method, nine groups of RPC specimens were designed and made by Ju [6-7]. According to the fast freezing test method of the long-term performance and durability test method of GBJ82285 normal concrete, 100 freeze-thaw cycle tests were carried out on RPC specimens. The effects of water binder ratio, silica fume cement ratio and steel fiber content on freeze-thaw properties of ordinary concrete and reactive powder concrete were explored. The results indicated that RPC had good freeze-thaw resistance. The water-binder ratio was the most critical factor, followed by the ratio of silica fume and cement, and the content of steel fiber.

Liu [8] performed freeze-thaw cycle tests on RPC prism specimens according to ASTMC666 standard (US rapid freeze-thaw test standard). The durability coefficient and mass loss rate are used to evaluate the frost resistance of concrete. After freeze-thaw cycles, the mass loss was about 0.3%, which was close to 0, and the durability coefficient exceeded 100.

Cwirzen [9] placed the RPC cube with a side length of 100mm and compressive strength of 130~202MPa into the 3% NaCl solution and conducted 56 freeze-thaw cycles. The study showed that the smaller the relative humidity inside the RPC specimens, the smaller the loss of the dynamic elastic modulus. The mass loss rate of the surface of the RPC specimens did not exceed 300g/m^2, some were lower than 200g/m^2. Thus, the requirement of the 200 years design life in the environment of freeze-thaw in Finland was satisfied.

Graybeal [10] conducted 690 freeze-thaw cycles of RPC, according to the “Standard test method for resistance of concrete to rapid freezing and thawing” (ASTM C 666). The mass loss rate of RPC after 28d standard conservation was 1.60~2.56%, the mass loss rate of RPC after 44h steam curing of 60~90°C was 0.07%~0.41%; the maximum dynamic elastic modulus of all the RPC specimens were not more than 4%, the maximum decrease of primary vibration frequency was not more than 5%.

2.2 Resistance chloride ion penetration

Roux [11] put the concrete with the thickness of 5mm(the cylinder compressive strength of the specimens with 100mm diameter and 200mm diameter were 35MPa and 90MPa respectively) and the disk-shaped RPC specimens into the electrochemical solution (distilled water for the anode, and the 0.5 Mol/L NaCl solution for the cathode), and applied the voltage of 12V, measured the migration power, respectively. The chloride ion diffusion coefficients of the three materials were 11×10^{-13}, 6×10^{-13}, and 0.2×10^{-13} m^2/s, respectively.

Graybeal [10], in accordance with the ASTM C1202, contacted one side of the cylindrical specimens of RPC with a diameter of 100mm, a height of 50mm to NaOH solution, and the other side to NaCl solution, and applied the voltage of 60V, measured the power through the specimen in 6 h was 18°C, then judged that the chloride ion permeability of UHPC can be ignored.

Peng [12] used the RCM method, tested the chlorine ion penetration of steel slag RPC and the compressive strength of cement mortar specimen was 120MPa, and compared with the C50 concrete with the water-binder ratio of 0.33, and found that: the chloride ion diffusion coefficient of steel slag RPC was 0.51×10^{-13}~$0.58\times10^{-13}m^2/s$, and the chloride ion diffusion coefficient of C50 concrete was 7×10^{-13}~$9\times10^{-13}m^2/s$.

Yu [13] test the electric flux of cylinder RPC with the compressive strength of 110.3~120.9MPa, according to ASTM C1202 “Standard test method for electrical indication of concrete s ability to resist chloride ion penetration”, the results showed that: the permeability of RPC increase with the decrease of the content of silica fume. The power through the RPC specimens in 6 h are all below 60C in different groups, lower than the concrete of 1~2 orders of magnitude, while chloride ion permeability can be ignored.

Wang [14] reported the durability of reactive powder concrete with the compressive strength of 150MPa under chloride-salt freeze-thaw cycling. The mass-loss rate was 0.62 % after 1500 freeze-thaw cycles in a 5.0 wt% NaCl solution and the relative dynamic-elastic modulus varied from 98 to 102%. The compressive strength of reactive powder concrete after 1000 and 1500 chloride-salt freeze-thaw cycles decrease by 17.3 and 41.6%, respectively.

2.3 Corrosion resistance

Liu [8] immersed RPC specimens, whose compressive strength of cement mortar was about 200MPa, into the mixed solution of 17.62% NaCl, 0.17% $CaCl_2$, 1.07% $MgCl_2\cdot6H_2O$ and 7.32% $MgSO_4\cdot7H_2O$. After 90 days, the mass loss of RPC was 0, the loss of dynamic elastic modulus was only 0.5%. This is because the hydration reaction of mineral admixtures created a dense RPC structure and the crack resistance effect of steel fiber.

Li [15] loaded the RPC blocks whose size were 100mm×100mm×400mm to 60, 70, and 80% of the compressive strength and then unloaded, then put them into 5% Na_2SO_4 solution and conducted 60 times of the wet-dry cycle. The test results showed that: the basic natural frequency of all the RPC blocks was increased at first and then decreased. But all of them were higher than the values when the test started in the end; the most significant decrease in the mess of the blocks was no more than 0.3%.

Song [16] conducted 20 dry-wet cycles of the RPC blocks whose side length was 100mm, and the cube compressive strength was 125MPa (a cycle means soaked in the Na_2SO_4 for 24h and drying for 24h in the drying oven of 80℃), the studies showed that: the mass loss of RPC blocks were around 1%, but the strength increased, indicating that the active admixtures can improve the sulfate corrosion resistance of RPC significantly.

2.4 Carbonation resistance

Wei [15] conducted the accelerated carbonation test of RPC whose fly ash content accounted for 48%. When the concentration of CO_2 was 60 %, the temperature was 20℃， and the relative humidity was 70%, the carbonation depth of RPC at 28d is 0, The carbonation depth of C80 concrete was 1.3~1.5mm in the same test conditions.

Roux [11] tested the natural carbonation and accelerated carbonation of normal concrete with the diameter of 110mm, the height of 220mm and the cylinder compressive strength of 35MPa and the RPC with the diameter of 70mm, the height of 140mm and the cylinder compressive strength of 170~230MPa. The results showed that: the carbonation coefficient of normal concrete is $50mm/yr^{0.5}$, but the RPC placed in the 100% CO_2 after 90d, the depth of carbonation is 0.

2.5 Abrasion resistance

Roux [11] obtained the wear resistance coefficient of C30, C80, and RPC200 concrete by a wear resistance test. The coefficient of wear resistance is characterized by the ratio of the wear rate of the specimen to the wear

rate of the glass. The results showed that the wear resistance coefficient of RPC200 was only 1.3, which was comparable to that of cement mortar made of Emery (wear resistance coefficient is 1.2).

The wear coefficient of regular concrete (RC), high strength mortar (HSM), and reactive powder concrete (RPC) was measured by Lee [17]. The wear coefficient is obtained under 500 and 1000 wear cycles. The results indicated that the wear coefficients of RC, HSM and RPC were 0.68, 0.86 and 0.95, respectively, under 500 wear cycles, and 0.33, 0.67 and 0.92, respectively, under 1000 wear cycles.

3. Durability mechanism of reactive powder concrete

Although the above studies used different tests and indicators for the investigation of RPC durability, however, all of the results show that the durability of RPC is superior to that of high strength concrete and ordinary concrete. The reasons are as follows:

1) The low water-cement ratio of RPC makes the number of gel pores, capillaries and connected pores in concrete very small. No coarse aggregate is added to improve the fineness of the components, and many kinds of active admixtures with different particle sizes and graded sand are added to optimize the particle gradation, which makes the concrete structure compact, uniform in texture and reduces the internal defects (pores and micro-cracks) of the concrete. Test results using mercury injection method indicated the porosity of RPC is very low, and most porosities are internal and harmless porosity [13]. For the reasons mentioned above, RPC has good impermeability. Capillary water and toxic ions are difficult to enter the concrete, and the channel of corroded concrete is blocked.

2) The pozzolanic effect of silica fume, slag, fly ash, and other active mineral admixtures is also one of the main reasons for the high durability of RPC. Because silica fume and other mineral admixtures are rich in SiO_2 or Al_2O_3, the reaction of $Ca(OH)_2$ with SiO_2 and Al_2O_3 reduce the content of $Ca(OH)_2$ and form stable hydrated calcium silicate with high strength. Especially under the condition of heat curing, most of $Ca(OH)_2$ is converted into hydrated calcium silicate. On the other hand, calcium silicate hydrated gel forms a protective layer on the surface of aluminum-containing compounds, which reduces the RPC erosion caused by harmful ions.

3) The excellent wear resistance of RPC can be attributed to two aspects. For one thing, RPC is usually made of quartz sand. The content of SiO_2 in quartz sand is more, the strength and hardness of quartz sand are higher than that of ordinary sand. Quartz sand is the most significant component in particles of RPC; its excellent wear resistance helps to improve the wear resistance of RPC. Besides, the high compactness caused by the extremely low water-cement ratio of RPC and the microaggregate filling effect and the pozzolanic effect, which improve the internal pore structure, interface structure of concrete, and the wear resistance of RPC.

4. Conclusions

From the review of the above studies, it can be seen that extensive research on both durability tests and mechanism analysis at home and abroad in recent years, and some achievements have been achieved. However, there are still some problems to be solved.

(1) The quantitative relationship between high-performance durability, mix ratio parameters and curing conditions need to be further investigated. The strength and fluidity of RPC are affected by water-cement ratio, sand content, admixture amount of active minerals, a variety of components, curing system, and so on. Whether the change of these conditions will affect the durability of RPC, if so, the degree of influence of various factors on RPC durability needs to be studied.

(2) Study on durability under multi-factor coupling. In the real environment, multiple erosion factors exist

at the same time. For example, in the splash zone and tidal range in marine environment， there are three kinds of erosion, chloride ion erosion, sulfate ion erosion, and dry-wet cycle. There is a freeze-thaw cycle along the northern coast of China. Therefore, multiple erosion factors should also be considered in the durability study of RPC.

(3) The problems of microstructure and mechanisms. The microstructure of RPC remains to be thoroughly studied, and the formation mechanism of its structure and strength is not fully understood.

(4) There is a lack of research on the durability of RPC components. The durability design theory and method of RPC structure or component need to be developed and perfected.

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