Review of research on durability of reactive powder concrete

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Abstract. Insufficient durability is an important reason why sustainable concrete materials cannot be achieved. Reactive Powder concrete (RPC) has attracted wide attention of researchers due to its excellent durability. Therefore, a series of researches on the durability of RPC have been carried out in order to achieve sustainable development of concrete. Therefore, based on the research results of domestic and foreign scholars, the durability of reactive powder concrete is comprehensively discussed from two aspects: single factor effect and multi-factor coupling effect. Judging from the research results, whether under the action of single factor or multi-factor coupling, reactive powder concrete has shown extraordinary durability performance, which proves its feasibility in creating durable concrete engineering; By summing up the existing research results, we also found its shortcomings, mainly including the lack of research on multi-factor coupling effects, especially the load-environment coupling effects, the lack of a micro-level description of the damage process, and the damage theory model is not yet clear, Evaluation methods, indicators are still to be studied and lack of actual data support and other issues.

1. Introduction
As the world's largest building material, concrete has been widely used in urban construction, highways, bridges, airports, dams, tunnels, underground, offshore engineering and other infrastructures in various countries, especially in China. Chinese "One Belt, One Road" development strategy is a new climax in the development of global infrastructure. In recent years, Chinese concrete output has continuously maintained more than half of the world's total output. In 2018, China's cement output was 2.177 billion tons, accounting for 55.11% of the global total production. As a key component of concrete, the production of cement is a process of energy-consuming materials, high carbon emissions, and large environmental load. The resource, energy and environmental problems caused by the widespread use of concrete are increasingly apparent. Resources and energy are the foundation of human future development, and the environment is the prerequisite for human beings to live in good health. In order to achieve sustainable development of resources and energy, research on sustainable concrete materials must be carried out from now on.

There are many concepts about sustainable development, but what is most acceptable to the public is the definition of the World Commission on Environment and Development in Our Common Future: Sustainable development is to meet the needs of contemporary people without harming the ability of future generations to meet their needs. Wu [1] once proposed that one of the two major problems facing cement concrete in the 21st century is the sustainable development of concrete. Jin [2] believed that the comprehensive value evaluation of sustainable development of concrete should be carried out...
through five aspects: ecological environmental protection benefits, economic benefits, living environment, architectural aesthetics and concrete durability. Müller [3] and others believe that to improve the sustainability of building structures is necessary to maximize the durability of the structure while reducing the environmental load. Mehta [4] proposed that the sustainable development of concrete should follow the following principles: saving the use of concrete raw materials and improving the durability of concrete structures. Jiang [5] proposed that the technical principles for the development of sustainable concrete should include: reducing the load of concrete raw materials on the environment, improving the durability of concrete, strengthening the repair and maintenance of concrete, and efficiently recycling waste concrete.

From the above definition of sustainable concrete materials, durability is considered to be a must. Excellent durability means a longer service life, less repair and maintenance costs, and good comprehensive economic benefits, so ensuring the durability of concrete structures to a certain extent achieves the sustainable development of concrete materials. Reactive powder concrete is a very innovative ultra-high-performance concrete. It achieves a great leap in material properties, and has both excellent mechanical and durability properties, excellent environmental protection, comprehensive economic performance, and conformance to for continuous requirements [6-8], as shown in Tables 1 and 2.

**Table 1.** Ecological performance comparison of different concretes under the same bearing capacity

| Type             | NC-30 | HPC-60 | RPC200 |
|------------------|-------|--------|--------|
| Equivalent section thickness (mm) | 500   | 400    | 150    |
| Equivalent volume (m³)          | 126   | 100    | 33     |
| Cement dosage (t)              | 44    | 40     | 23     |
| Carbon dioxide emissions (t)    | 44    | 40     | 27     |
| Aggregate dosage (t)            | 230   | 170    | 60     |

**Table 2.** Comparison of RPC with high performance concrete and ordinary concrete

| Index                        | RPC        | HPC        | NC       |
|------------------------------|------------|------------|----------|
| Mechanical properties        |            |            |          |
| Compressive strength (MPa)   | 140-150    | 60-100     | 20-50    |
| Tensile Strength (MPa)       | 6-8        | 4-6        | 3-4      |
| Flexural Strength (MPa)      | 20-30      | 6-10       | 2-5      |
| Elastic Modulus (GPa)        | 40-45      | 30-40      | ≤35      |
| Fracture energy (KJ/m²)      | 20-30      | 0.14       | 0.12     |
| durability                   |            |            |          |
| chloride diffusion coefficient (10⁻¹³/s) | 0.02  | 0.6       | 1.1      |
| Freeze-thaw peeling (g/cm²)  | 7          | 900        | ≥1000    |
| carbonation depth (mm)       | 0          | 2          | 10       |
| Wear coefficient             | 1.3        | 2.8        | 4        |

It can be seen from the above that the preparation of RPC not only consumes less energy, but also occupies less non-renewable aggregate resources. Moreover, it has excellent durability and fully meets the requirements of sustainable concrete materials. It is an important supporting material for achieving sustainable development of concrete structures. The importance of durability to achieve sustainable development is self-evident, so we should focus on its durability here. By analysing and studying the causes of concrete structure damage, the mechanism that affects its durability is obtained, as shown in Figure 1.
2. Research Status of Durability of Reactive Powder Concrete

By summarizing the existing research results on the durability of reactive powder concrete, it was found that the researchers mainly carried out research on single-factor effects and multi-factor coupling effects.

2.1. Study on durability performance under single factor

It is found that the research on the durability of single factors mainly focuses on the effects of freeze-thaw, carbonization, and resistance to chloride ions, wet-dry cycles and chemical erosion and so on.

Graybar [9] tested RPC specimens subjected to 690 freeze-thaw cycles and found that the RPC mass loss rate for standard curing 28d was 1.60%~2.56%, and the RPC mass loss rate after steam curing at 60~90°C for 44h was 0.07%~0.41%, and the maximum loss rate of the dynamic elastic modulus of all test blocks does not exceed 4%, which shows excellent freeze resistance. Ming-Gin Lee [10] used RPC as a repair material and studied its durability and found that after 1000 freeze-thaw cycles, its compressive strength is slightly reduced. De-hui Wang [11] found that after 1,000 freeze-thaw cycles, the relative dynamic modulus of ordinary concrete, high-strength mortar, and RPC decreased by 61%, 22%, and 10%, respectively, and the compressive strength decreased 57%, 16%, and 6%. In addition, the bond strength of the steel to the substrate was reduced by 35%, 23%, and 5%, respectively.

Shi [12] measured the chloride ion resistance of RPC with reference to ASTM C1202. The results show that the passing power of RPC specimens within 6h is below 30C, which is 1~2 orders of magnitude lower than that of ordinary concrete. The experimental results of Graybar [9] show that its 6h electric flux is only 6C, which is considered to be negligible.

N. Roux [13] stored the RPC specimens in 100% CO₂ for 90 days, and found that the specimens were not carbonized at all; Liu JH [14] tested the carbonization depths of 28d and 56d of RPC with different cement dosages, and found that when the cement dosages were 500, 400, and 300 kg/m³, the carbonization stayed only on the surface of the specimen, and the carbonization depths were all 0mm; In addition, G. C. Long [15] researched the carbonization of UHPC under different curing conditions and found that UHPC will not carbonize regardless of sealing, standard and heat curing.

Ning [16] carried out a study on the resistance of RPC to sulphate attack and found that the strength of RPC specimens soaked in sulphate solution were increased by 16.2% compared to that in water soak, and the coefficient of RPC’s resistance to sulphate attack was 116.5%; Peng [17, 18] put RPC specimens with compressive strength of 187.0 MPa and 190.3 MPa into a 5% Na₂SO₄ solution for 150
wet and dry cycles, and found that the mass loss was almost zero, and the compressive strength and corrosion resistance coefficients exceeded 98%.

2.2. Study on durability under multi-factor coupling

With the development of research, people gradually realized that it is not enough to evaluate the durability of concrete structures by using a single factor. The actual engineering environment is often complicated, usually multiple factors are integrated, so people have launched a multi-factor coupling effect to evaluate the durability of RPC, mainly including freeze-thaw cycles and chloride ion erosion, loads and freeze-thaw cycles, dry and wet cycles coupling effects of chloride ion erosion, dry-wet cycle and alkali aggregate reaction and so on.

Wang [19] carried out a seawater freeze-thaw cycle test on RPC with compressive strength of 112.5-156 MPa of a cube with a side length of 100mm, and compared it with C50 ordinary concrete. The results show that when the freeze-thaw cycle reaches 250 times, the compressive strength of C50 concrete decreases by 26.2%, and when the freeze-thaw cycle reaches 800 times, the RPC compressive strength does not decrease by more than 25%; An [20] believes that the service life of activated powder concrete exceeds 90a under the action of seawater freeze-thaw cycle, while the service life of C50 high-performance concrete is only 24.4a. In addition, they also studied the resistance of RPC to chloride ion penetration under external load conditions. The results show that when the load is over 60%, the chloride ion mobility coefficient increases rapidly, that is, the RPC itself and the damage show good resistance to chloride ion permeability when the load is less than 60%.

Ye [21] studied the sulphate resistance of RPC and HSC at 28d in two different wet and dry conditions, and she found that the compressive strength and erosion resistance coefficient of RPC is 8% higher than that of HSC under the cycling mechanism in 20% (NH₄)₂SO₄ erosion medium and the compressive strength and erosion resistance coefficient of RPC is higher than HSC 16% higher under the cyclic mechanism in 5 times artificial seawater erosion medium. It can see that the corrosion resistance of RPC is better than that of HSC under the action of chemical solution-dry-wet cycle.

Jia [22] carried out the freeze-thaw-chlorine salt (3.5% NaCl solution) coupling effect on the durability of reactive powder concrete. And the test results show that with the increase of the number of couplings and freeze-thaw cycles, the chloride ion content at different depths of the RPC specimen gradually increases. When the freeze-thaw cycle reached 600 times, the chloride ion permeability coefficient reaches 0.147%; as the coupling times increase, the RPC compressive strength gradually decreased. After 800 times of coupling, the RPC compressive strength even decreased by 22.9% ~ 37.9%.

An [23] studied the frost resistance of damaged specimens by using the single-sided freeze-thaw method. The test results show that the damage will reduce the freeze-thaw resistance of the test piece. The greater the degree of damage, the more the freeze-thaw resistance is reduced.

Li [24] loaded the RPC specimens to 60%, 70%, and 80% of their compressive strength, unloaded them, and then placed them in a 5% Na₂SO₄ solution for 60 wet and dry cycles. The results show that the basic natural frequency of the RPC specimens is higher than the initial basic natural frequency, and the maximum quality of the specimens does not exceed 0.3%.

Xu [25] carried out a study on the durability of 120MPa RPC under the coupling of sulfate-dry-wet cycle (dry 8d + sodium sulphate solution 7d) -bending stress loading. The test results found that after 90 days of immersion in a 10% sulfate solution, the relative dynamic elastic modulus of the specimen was 1.075, and after six sulfate dry and wet cycles (10%), the relative dynamic modulus of RPC was 1.04; and When 50% bending stress is applied to it, relative dynamic elastic modulus of the specimen is 1.01, which indicates that the damage rate of RPC is accelerated under the coupling of three factors.

3. Conclusion

It can be seen from the above studies that, regardless of single factor or multi-factor coupling, reactive powder concrete shows excellent durability, far exceeding ordinary concrete and high performance
concrete. Although scholars at home and abroad have conducted a lot of research on the properties of reactive powder concrete and achieved certain results, there are still some problems that need to be solved urgently.

(1) The durability research under the coupling of multiple factors is still to be completed. The actual engineering service not only faces the coupling environment of two factors, but may be three or even more. How to clarify the relationship between the primary and secondary and the sequence under this comprehensive effect; And concrete structures work under the combined action of load and environment, and the load may cause the physical properties of the concrete to change, which will affect the durability of the concrete structure. The study results of concrete durability obtained by neglecting the load have some one-sidedness Therefore, it is necessary to pay attention to the role of load, and the corresponding test equipment also needs to be developed.

(2) The micro-mechanism is still lacking. The change of the macro performance is the reflection of the change of the microstructure. As reactive powder concrete is a multi-component material, the study of its microstructure evolution regular can better reveal the deterioration regular of concrete and lay the foundation for people to design durable concrete materials according.

(3) The existing durability evaluation methods and indicators still need to be improved. The durability research methods of reactive powder concrete still refer to the ordinary concrete durability test methods, the test methods and evaluation indexes of various properties are diverse, but many methods and indexes are not applicable. For example, under the freeze-thaw-sulfate coupling effect, the relative elastic modulus is less sensitive than compressive strength [26], and the compressive strength is not as good as split tensile strength [27].

(4) The study of theoretical models has yet to be perfected. At present, most studies are based on experiments, and most of them are qualitative conclusions. There are few conclusions about damage mechanism models and corresponding quantitative relationships. In order to make better use and design of reactive powder concrete, it is necessary to strengthen the research on the relationship between durability affecting factors and concrete damage parameters. Based on qualitative research, a quantitative relationship is established to analyse the damage evolution and damage of concrete process to determine the critical value of damage. According to the damage evolution equation, the service life and prediction of materials and structural components are further determined.

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