Study on the Durability of Ultra-High Performance Concrete in Extreme Environment

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Abstract. In the field of civil engineering, with the rapid development of global climate change and industrialization, the durability of building materials has presented unprecedented challenges. For this challenge, this paper innovatively studies the durability of ultra-high performance concrete (UHPC) in extreme environmental conditions. Through systematic experimental research and theoretical analysis, this study discusses the remarkable effect of fiber enhancement, nanomaterials application and surface treatment technology in improving UHPC durability, and proposes an improvement scheme for the existing durability test method. The experimental results revealed that the UHPC modified by carbon nanotubes showed excellent performance in resisting freezing and thawing and salt erosion, while the application of waterproof layer significantly improved the durability of UHPC. In addition, this study also proposed comprehensive protection measures, including fiber enhancement, waterproof layer and anticorrosive coating, which can significantly improve the durability of UHPC in extreme environments. The study also looks into the future to further optimize the UHPC design and improve its application performance in various extreme environments to promote the wide application and development of UHPC in the civil engineering field. The findings of this study not only provide the theoretical basis and technical support for the wide application of UHPC in extreme environments, but also provide new solutions for realizing the sustainable utilization of resources, which has important scientific significance and application value.

Keywords: ultra-high performance concrete (UHPC), durability, freeze-thaw cycle, salt erosion, extreme environment.

1 Introduction

Globally, civil engineering structures are facing the dual challenges of increasing climate change and the industrialization process. These challenges place higher demands for the durability of the structures, especially in extreme climatic conditions. The stability and safety of critical infrastructures such as bridges, tunnels and ocean

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engineering are directly influenced by these environmental factors[1]. In recent years, ultra-high performance concrete (UHPC) has attracted wide attention due to its excellent mechanical properties and durability, and has shown great application potential in the field of civil engineering[2]. The high strength, high toughness, and excellent durability and corrosion resistance of UHPC make it an ideal material[3] for applications in extreme environments.

However, despite the significant advantages of UHPC in many aspects, there are still many challenges in its durability research in extreme environments, especially the performance of [4] in natural conditions such as freeze-thaw cycles and salt erosion. Free-thaw cycle will cause the expansion of moisture inside concrete to forming microcracks; and salt erosion may accelerate the corrosion process of reinforcement in concrete[5]. Therefore, deeply studying the impact of these extreme environmental factors on UHPC performance is important to improve their application performance in harsh climatic areas.

In response to this challenge, this paper discusses the effectiveness of fiber enhancement, nanomaterials application and surface treatment technology in improving UHPC durability[6]. This study aims to propose improvements through experimental research and theoretical analysis to improve the durability of UHPC in extreme environments and to evaluate the advantages and disadvantages of existing durability testing methods[7].

The structure arrangement of the paper is as follows: first, introduce the basic knowledge of UHPC and the difference from traditional concrete; then analyze the influence of extreme environment on the durability of UHPC[8]; then discuss the material design strategy to improve the durability of UHPC; then introduce the evaluation method of UHPC durability; verify the above theoretical analysis through experimental research; and finally summarize the experience and lessons in practical application through case study, and prospect the future research direction. This paper expects to provide more valuable reference information for the application of UHPC in extreme environments.

2 Research Progress and Application Prospect of Ultra-High Performance Concrete (UHPC)

Ultra-high performance concrete is a kind of special concrete with extremely high mechanical properties and durability. Its main components include cement, fine sand, quartz powder, steel fiber[9] or polymer fiber. UHPC achieves higher strength, toughness and durability[10] than conventional concrete through finely designed mixture proportions and strict construction techniques. Its typical characteristics include: (1) compressive strength is greater than 85MPa; (2) folding strength is greater than 20MPa; (3) fracture toughness is greater than 5000J / m^2; (4) low porosity and high compactness.

Compared with UHPC traditional concrete, UHPC has shown obvious advantages in the following aspects:

Mechanical properties: UHPC has higher compressive strength and folding strength, and can withstand greater load;

Durability: UHPC has lower porosity, higher density, stronger freeze-thaw resistance and corrosion resistance;

Toughness: UHPC improves its fracture toughness and enhances the ductility of materials by adding fibers;

Construction performance: UHPC has good mobility, easy to pump and pour, and high surface finish after hardening.

In recent years, with the deepening of UHPC research, UHPC research[11-12] has been increasingly widely used in bridge, tunnel, ocean engineering and other fields. In the future, with the development of new fibrous materials, nanotechnology and intelligent monitoring methods of[13], UHPC shows great potential in emerging fields such as space architecture and deep-sea structure. Future studies will continue to explore the long-term performance of UHPC in extreme environments and develop more environmentally friendly and sustainable building materials to meet the needs of future civil engineering.

3 Effect of Extreme Environments on UHPC Durability

Free-thaw cycle refers to the process of repeated freezing and melting, the internal water freezes and expands, leading to the formation and expansion of micro-cracks, thus affecting its durability. The study shows that UHPC is more frost resistant than conventional concrete due to its low porosity and high density. However, under extreme low temperature conditions, microcracks may still appear in UHPC, especially under repeated freeze and thaw cycles, the number and size of cracks will gradually increase. Therefore, it is important to study the effect of freeze-thaw cycle on the durability of UHPC to improve its application performance in cold areas.

Salt erosion refers to the erosion effect of seawater, saline-alkali soil and other saline media on the concrete structure. The salt enters the concrete through the pores, accelerating the corrosion of steel bars, resulting in the decline of structural performance. Due to its high density and low porosity, UHPC has better salt erosion resistance than traditional concrete. But long-term exposure to high salt[14], UHPC may also be eroded. Therefore, studying the effect of salt erosion on the durability of UHPC is crucial to improve its application performance in coastal and saline areas.

In addition to the freeze-thaw cycle and salt erosion, other extreme environmental factors such as chemical erosion (sulfate erosion, acid rain erosion, etc.) and temperature changes can also affect the durability of UHPC. Chemical erosion will change the chemical composition of concrete and reduce its mechanical properties; temperature change will affect the shrinkage and expansion of concrete, leading to the formation of microcracks. Therefore, a comprehensive study of the impact of extreme environments on UHPC durability is important to improve its application performance in complex environments.

4 Material Design Strategy for UHPC Durability Improvement

In order to improve the durability of ultra-high performance concrete (UHPC), various material design strategies were adopted, including fiber enhancement, nanomaterials application, and surface treatment and coating techniques.

4.1 Fiber Enhancement

By adding steel fibers or polymer fibers into UHPC, we successfully improve its fracture toughness and crack resistance. The distribution of fibers in the UHPC matrix forms an effective microfracture inhibition mechanism that delays the fracture expansion and thus significantly improves the durability of the material. In addition, the addition of fibers also improves the plastic deformation ability of UHPC[15], enabling it to show better ductility in the stress state, which is crucial to withstand extreme temperature changes and mechanical shocks.

4.2 Application of Nanomaterials

The application of nanotechnology is one of the key strategies to improve UHPC durability. We investigated the effects of nanomaterials such as silicon powder and carbon nanotubes on UHPC properties. Because of their high specific surface area and activity, these nanomaterials can effectively fill the micropores inside the concrete, thus improving the compactness and impermeable[16]. In addition, nanomaterials can also promote the hydration of cement slurry and accelerate the early development of UHPC strength. The experimental results show that the freezing and thawing resistance and chemical erosion resistance of UHPC were significantly improved by adding appropriate nanomaterials.

4.3 Surface Treatment and Coating Technology

To further enhance the durability of the UHPC, we have also explored the surface treatment and coating techniques. By applying a waterproof coating, anticorrosive coating, and surface hardening treatment on the UHPC surface, we have successfully prevented the invasion of the external erosion media. The waterproof coating can effectively prevent the penetration of moisture and harmful substances; the corrosive coating improves the corrosion resistance of UHPC[17]; and the surface hardening treatment enhances the wear resistance and impact resistance of UHPC through chemical reaction. These surface protection measures are essential to improve UHPC durability in extreme environments.Hybrid machine learning (ML) techniques can be used to predict the autogenous shrinkage (AS) of ultra-high-performance concrete (UH). The steel fiber content (SFS) is a highly influential feature for predicting AS[18].Ultra-high performance concrete (UHPC) is known for its excellent durability and strength due to its dense microstructure. The applied load level, cover, and compressive strength have a significant impact on the behavior of UHPC, and the strength of the concrete can be improved by adding a concrete cover[19].Pure water and chloride-containing seawater have a significant impact on the self-healing performance and corrosion resistance of embedded rebars in both cracked and unacked ultra-high performance concrete (UHPC) specimens[20].The fiber arrangement of UHPC affected by the boundary effect has certain regularity, and this research finding provides valuable insights for the design of DP-UHPC to improve fiber reinforcement efficiency[21].

Using a combination of fiber augmentation, nanomaterials, and surface treatment techniques, we significantly improve the durability of the UHPC to better adapt to the challenges of extreme environments. These strategies not only improve the mechanical properties and durability of the UHPC, but also enhance its applicability and economy in practical engineering. Future studies will further optimize these material design strategies to enable UHPC applications in a wider range of settings.

5 Methods for Assessing UHPC Durability

Accurate assessment of the durability of ultra-high performance concrete (UHPC) is key to ensuring long-term service in extreme environments. Currently, the experimental methods for assessing UHPC durability mainly include the following:

5.1 Free-Thaw Cycle Test

This test evaluates the freezing resistance of UHPC by simulating the freeze-thaw process in the natural environment. The specimen is periodically converted between a set low temperature (usually-20°C) and room temperature (usually + 20°C), with each cycle usually lasting for 24 hours and multiple cycles to simulate the long-term effect. The core of the freeze-thaw cycle test is that it can effectively reflect the performance changes of UHPC in alternating cold and heat environments. As the number of cycles increases, the water inside the specimen expands during freezing, which may lead to the formation and expansion of microcracks, thus affecting the overall strength and durability of concrete. Therefore, through the test of the appearance changes, mass loss and mechanical properties of the specimen after the freeze-thaw cycle.

5.2 Salt Erosion Test

By simulating the Marine or saline environment, the UHPC specimens with saline solution are soaked to evaluate their salt erosion resistance. In the test, the specimen was placed in a 5% NaCl solution to simulate the erosion effect of seawater on concrete. The salt enters the inside through the pores of the concrete, accelerating the corrosion of the steel and the degradation of the concrete. Therefore, the observation and test of the mass loss, surface cracks and mechanical properties changes of the specimen under salt erosion conditions can effectively evaluate the durability of UHPC in the saline environment.

For both tests, the initial status of the specimen and a detailed testing after each cycle or immersion phase. By comparing the performance of test specimens under different conditions, researchers can deeply analyze the performance of UHPC in extreme environments, and then propose improvement measures.

In addition, the freeze-thaw cycle test and the salt erosion test each have their own advantages and disadvantages. The advantage of the freeze-thaw cycle test is that it can simulate the common temperature changes in the natural environment, but it has a long period and has high requirements for equipment. Salt erosion test is relatively simple and can quickly assess the durability of concrete under salt erosion, but the results may be affected by the specimen surface treatment and environmental conditions.

In conclusion, the freeze-thaw cycle test and salt erosion test are important methods to assess the durability of UHPC, and these experiments can provide scientific basis for the design and application of UHPC and ensure its long-term stability and safety in extreme environments. Future studies will continue to explore more efficient assessment methods to meet the demand for high-performance materials in the civil engineering field.

6 Experimental Research

This experiment is carried out through the traditional experimental method, through the preparation of test block, standard breeding and experiment.

6.1 Experimental Design and Methodology

Material preparation

To ensure the accuracy and reliability of the experimental results, we selected the standard UHPC mix ratio for the specimen preparation. The specific material composition is as follows:

Cement: ordinary Portland cement P · O 52.5R in a factory in Mengxi, density is 3.1 g / cm^3, initial setting time is 2.5 h and final setting time is 5 h.

Fly ash: primary fly ash in a power plant in Ordos

Fine sand: Ordos produces river sand with a grain diameter of 0.15 mm~0.3 mm, and the water content is less than 0.5%.

Silicon powder: the particle size of Wenbang, Zhengzhou, Henan province is 0.045 mm, and the purity is greater than 99%.

Steel fiber: produced in Langfang, Hebei province, length of 30 mm, diameter of 0.2 mm, tensile strength of 1200 MPa, volume volume of 1%.

Carbon nanotubes: a manufacturer in Beijing, specification 5um.

Water: clean tap water, with a pH value of 7.0.

Adxture: Shaanxi efficient water reducing agent, mixed for 1% of the weight of cement.

Test mix: 550g of cement, 270g of fly ash, 130g of silicon powder, 400 Kg/m3 of steel fiber, 0.15% of carbon nanotubes.

The preparation step of the specimen is as follows:

Material weighing: accurately weigh each component material according to the mix ratio.

Dry mixing: first mix the dry mixture in the mixer for 2 minutes to ensure the uniform distribution of each component.

Add water: add quantitative clean tap water to the mixer slowly and stir for 3 minutes.

Pouring: Pour the mixed UHPC into the prepared mold for vibration dense.

Maintenance: The specimen is maintained for 28 days under standard curing conditions (temperature 20°C ± 2°C, humidity above 95%).

The test piece size is 100mm 100mm 400mm, a total of 150 specimens were prepared, divided into five groups, each group of 30 specimens, respectively used for strength experiment, freeze-thaw cycle, salt spray erosion, freeze-thaw + salt spray erosion and other tests, waterproof layer.

Experiment condition

Freeze-thaw cycle test: Simulate the freeze-thaw cycle in the natural environment, place the specimen in-20°C to + 20°C for 24 hours for 250 consecutive cycles.

Salt erosion test: to simulate seawater or saline soil environment, place the specimen in a salt penetration tank containing 5%NaCl solution with water flow of 5 m / min.

Salt erosion and freeze-thaw test: put the temperature above zero in the simulated 5%NaCl salt penetration tank, with water flow of 5 m / min. Put the brine bubble in the test mold when the temperature is below zero.

Test method

Compressive strength test: use the hydraulic universal test machine to conduct the compressive strength test under the standard curing conditions (temperature 20°C ± 2°C, humidity above 95%).

Free-thaw cycle number test: record the appearance change of the specimen after the freeze-thaw cycle test, and measure the change of the compressive strength and folding strength.

6.2 Analysis of the Experimental Results

Pecsive Strength Results:

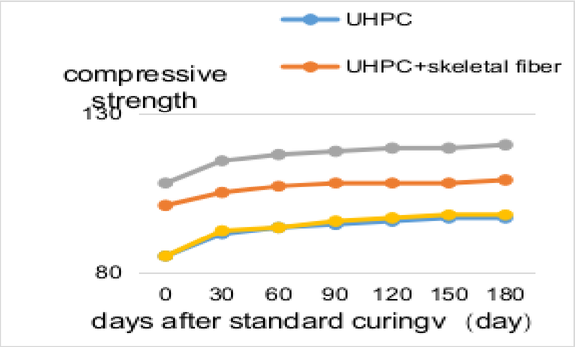

Fig. 1. Strength change diagram of the end of standard breeding

Figure 1 shows that with the end of the concrete standard breeding, the strength is still increasing slowly.

Results of the freeze-thaw cycle test

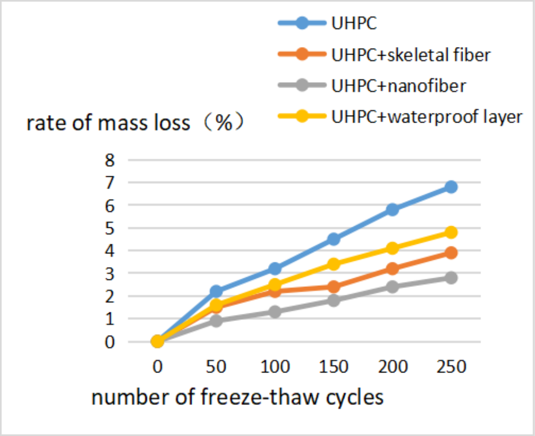

Fig. 2. Plot of mass loss rate of freeze-thaw cycle

Fig.2 shows that with the increase in the number of freeze-thaw cycles, the mass loss rate is higher.

It can be seen that the mass loss rate of UHPC specimens gradually increased with the increase of freeze-thaw cycles, with the maximum 7% and the minimum after 250 cycles being 2.8. Carbon nano UHPC <steel fiber UHPC <waterproof layer UHPC <UHPC.

Salt erosion test results

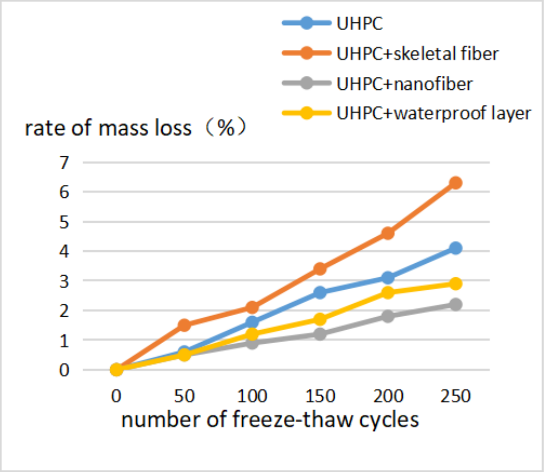

Fig. 3. Mass loss rate on the days of salt invasion

Fig.3 shows, with the increase of the days of salt intrusion, the mass loss rate of various test blocks is also increasing. The loss rate was 6.3% and the smallest loss rate was 2.2%. Moreover, we observed some degree of erosion on the specimen surface, but the internal structure remained intact. After 7 days of erosion, some white salt cream appeared on the surface of the specimen, but it did not affect the overall structure. Carbon nano UHPC <waterproof layer UHPC <UHPC <steel fiber UHPC.

Results of salt erosion ice melting test

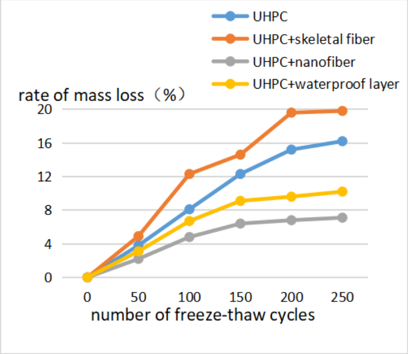

Fig. 4. Mass loss rate of salt-eroded ice melting

Fig.4 shows, with the increase of the days of salt intrusion, the mass loss rate of various test blocks is also increasing.Then the rate of UHPC specimens increases with increasing frequency. After 250 cycles, the maximum was 19.2% and the minimum was 7.1. Carbon nano UHPC <waterproof layer UHPC <UHPC <steel fiber UHPC.

In addition, we also observed different degrees of erosion on the specimen surface, and also some erosion on the internal structure of steel fiber UHPC.

6.3 Significance of the Experimental Results for the Design and Application of UHPC

The results of this experimental study are instructive for the design and practical application of UHPC. By comparing the performance changes of UHPC specimens under different conditions, the following key conclusions can be drawn:

Selection of fiber types: The experimental results showed that the performance of steel fiber UHPC and carbon nanotube UHPC in resisting freezing and thawing and resisting salt erosion was obviously different. Among them, carbon nanotubes UHPC performed better in terms of mass loss rate, indicating that the addition of carbon nanotubes can effectively improve the freeze-thaw and salt erosion resistance of UHPC. Therefore, in practical engineering applications, the appropriate fiber types and dosage can be selected according to the specific requirements to achieve the optimal durability effect.

The importance of waterproof layer: the experimental results show that the UHPC test piece with waterproof layer has excellent performance in freezing and thawing resistance and salt erosion resistance, and the quality loss rate is significantly lower than that of the specimen without waterproof layer. This indicates that the application of the waterproof layer can effectively improve the durability of UHPC in extreme environments. Therefore, in the practical engineering application, attention should be paid to the use of the waterproof layer, especially in the areas prone to freeze-thaw cycles and salt erosion.

Comprehensive protective measures: The experimental results show that, relying solely on the fiber enhancement or waterproof layer can not completely solve the durability problem of UHPC in the extreme environment. For example, under salt erosion and ice melting conditions, the mass loss rate of UHPC specimens is still high even with the addition of a waterproof layer. Therefore, in practical engineering applications, comprehensive protective measures should be taken, including but not limited to fiber reinforcement, waterproof layer, anticorrosive coating, etc., in order to comprehensively improve the durability of UHPC.

Optimized mix ratio: The experimental results also show that the durability of UHPC can be further improved by optimizing the mix ratio. For example, appropriately increasing the amount of silicon powder can significantly improve the freeze-thaw resistance and salt erosion resistance of UHPC. Therefore, in the practical engineering application, the mix ratio should be optimized according to the specific case to achieve the optimal durability effect.

Surface treatment technology: The experimental results show that a reasonable surface treatment technology can significantly improve the durability of UHPC in extreme environments. For example, the application of waterproof coatings and anticorrosive coatings can be effective in preventing the invasion of external erosion media. Therefore, in practical engineering applications, attention should be paid to the application of surface treatment technology to improve the overall durability of UHPC.

In conclusion, this experimental study reveals the performance changes of UHPC under different conditions, and provides a valuable reference for the design and practical application of UHPC. Future studies will further optimize the design of UHPC and improve its application performance in various extreme environments, thus promoting the wide application and development of UHPC in the civil engineering field.

6.4 Summary

In this study, a systematic experimental study and theoretical analysis of the durability of UHPC in extreme environments can draw the following conclusions:

Effect of freeze-thaw cycle: After 250 freeze-thaw cycles, the mass loss rate was up to 7%, while the carbon nanotube UHPC was the lowest, only 2.8%. This indicates that the addition of CNTs can significantly improve the freeze-thaw resistance of UHPC. In addition, the application of the waterproof layer has also significantly reduced the mass loss rate, demonstrating the importance of the waterproof layer in improving the UHPC durability.

Effect of salt erosion: In the salt erosion test, the mass loss rate of UHPC specimens was the maximum of 6.3% and the minimum was 2.2%. Carbon nanotube UHPC again showed superior durability with the lowest loss rate. This result highlights the role of CNTs in improving the salt erosion resistance of UHPC. At the same time, the application of the waterproof layer also effectively reduces the damage of UHPC caused by salt erosion.

Effectiveness of comprehensive protective measures: under salt erosion and ice melting conditions, the maximum mass loss rate of UHPC specimens reached 19.2%, while the loss rate of carbon nanotube UHPC and waterproof layer UHPC was 7.1% and 7.8%, respectively. This result indicates that comprehensive protective measures (such as fiber enhancement, waterproof layer, preservative coating, etc.) can significantly improve the durability of UHPC in extreme environments.

Improving assessment methods: The existing durability test methods have problems such as long time, high cost and uncertain results. Therefore, this study proposes the improved methods of accelerated test method, non-destructive detection and numerical simulation to improve the evaluation efficiency and accuracy. The application of these methods will facilitate a faster assessment of UHPC durability, reduce trial costs, and reduce outcome uncertainty.

Experience and lessons in practical application: Through the analysis of the experimental results, the performance changes of UHPC under different conditions can be found, which provides an important reference for practical engineering application. Future studies will further optimize the design of UHPC and improve its application performance in various extreme environments, thus promoting the wide application and development of UHPC in the civil engineering field.

In conclusion, this study revealed the durability characteristics of UHPC in the extreme environment, providing a valuable reference for the design and practical application of UHPC. Future studies will continue to explore more effective protective measures to further enhance the durability and application potential of UHPC in extreme environments.

7 Case Study

Case 1: Fuwingmen Bridge, Zhoushan Port, Ningbo

The high salinity and severe breeze erosion in southeast coastal areas of China pose severe challenges to the durability of buildings. In a bridge construction project, the engineers chose UHPC as the main material, and added steel fiber and waterproof layer in the construction process. After two years of use, the wharf structure performed well in a salt-eroded environment. Ensure the safety and stability of the bridge during its long-term service. This case shows that UHPC can demonstrate excellent durability in a high-salt environment through rational material design and technical measures.

Case 2: Ordos bridge expansion joint

In the bridge construction of Weijiamao in Ordos, because it is located in the north of China, near the Yellow River, there are many snow and vehicles, which puts forward special requirements for the durability of the structure of the expansion joint. In a project project, the designer selected UHPC as the expansion joint material, and added silicon powder and anticorrosive coating in the construction process. After many years of operation, the bridge is maintained in good structural condition, with no obvious cracks or other damage phenomenon.

From these two case studies, we can see that UHPC can show excellent durability in extreme environments through reasonable material design and technical measures. These experiences provide valuable references for the future construction and maintenance of similar projects.

8 Risk Assessment, Management, and Future Research Direction

In this study, we systematically explore the durability of ultra-high performance concrete (UHPC) in extreme environments, and make corresponding suggestions for improvement. In order to ensure the safety and reliability of UHPC in practical engineering applications, this section will evaluate the possible risks of UHPC application and propose corresponding management strategies. In addition, we will also explore future research directions to further optimize the application of UHPC.

Risk assessment and management

Although UHPC shows excellent performance in durability, the following risks are still needed in practical engineering applications:

Material cost risk: The cost of UHPC is higher than that of traditional concrete, which may affect the economic benefits of the project. It is recommended to reduce costs by scale production and optimizing the formula.

Construction technical risk: the construction technology requirement of UHPC is high, and improper construction may lead to substandard performance. It is suggested to strengthen the technical training of construction personnel, and formulate strict construction quality control standards.

Environmental adaptive risks: Despite UHPC performance advantages in extreme environments, unknown risks may occur under certain conditions. Long-term performance monitoring, timely evaluation and adjustment of the design scheme are recommended.

Maintenance and repair risks: Maintenance and repair technologies for UHPC are immature and may affect the long-term performance of the structure. Dedicated maintenance materials and repair techniques are recommended.

Management policy:

Develop a detailed risk management plan, including risk identification, assessment, monitoring, and response measures.

Establish a database of UHPC application, collect and analyze practical engineering cases, and provide data support for risk assessment.

Strengthen communication with material suppliers, construction units and maintenance teams to ensure the effective implementation of risk management measures.

Future research direction

Based on the limitations of the current study and the development potential of the UHPC, we propose the following future research directions:

Coupled pling of multiple environmental factors: the durability study of UHPC under the coupling of various extreme environmental factors (such as freeze-thaw cycle, salt erosion, chemical erosion, etc.).

Intelligent construction technology: explore the use of robots and automation equipment for UHPC construction, improve the construction quality and efficiency.

Full life cycle performance assessment: conduct UHPC performance assessment of the whole process from production, construction to use, to provide more accurate data support for engineering design.

Interdisciplinary materials design: Develop a new generation of UHPC materials combined with knowledge in materials science, environmental science, and civil engineering.

Environmental impact assessment: to assess the environmental impact of UHPC throughout the life cycle and explore more environmentally friendly production and construction methods.

International cooperation and standard formulation: cooperate with international peers to jointly develop the international application standards and specifications of UHPC.

Through the implementation of the above risk assessment and management strategy, and the in-depth exploration of future research directions, we can ensure the wide application and continuous development of UHPC in the civil engineering field. We expect that these research results can provide more theoretical basis and technical support for the design, construction and maintenance of UHPC, promoting the full play of its application potential in extreme environments.

9 Conclusion

This paper systematically investigates the durability of UHPC in extreme environments through experimental research and theoretical analysis, and draws the following conclusions:

The mass loss rate of UHPC can be as high as 7% after 250 freeze-thaw cycles, while the loss rate of carbon nanotube UHPC is the lowest, at only 2.8%.In the salt erosion test, the mass loss rate of the UHPC specimens was a maximum of 6.3% and a minimum of2.2%. The carbon nanotube UHPC again showed superior durability, with the lowest loss rate.Under the condition of salt erosion and ice melting, the mass loss rate of UHPC specimens was as high as 19.2%, the loss rates of carbon nanotube UHPC and waterproof layer UHPC were 7.1% and 7.8% respectively.

In summary, CNT-UHPC exhibits excellent performance in freeze-thaw resistance and salt erosion resistance, and the application of waterproof layers significantly the durability of UHPC. Meanwhile, comprehensive protective measures can also significantly enhance the durability of UHPC in extreme environments. Future research will further optimize the of UHPC, improve its application performance in various extreme environments, and promote the wide application and development of UHPC in the field of civil engineering.

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