Application of ultra-high performance concrete in the marine environment

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Abstract. The development and utilization of marine resources are becoming the focus of all countries. However, the special characteristics of the marine environment pose severe durability challenges to traditional concrete materials. Ultra-high performance concrete (UHPC) has gradually been widely used in marine engineering due to its excellent durability and corrosion resistance. This paper discusses the basic concept of UHPC and its mechanism of action, evaluates its current application in marine engineering, and analyzes the challenges of its application in the marine environment. On this basis, this paper looks forward to the future development direction of UHPC in marine engineering, pointing out that with the progress of material science and construction technology, UHPC will play a greater role in the research and development of new types of structures and the improvement of construction technology, and promote its wide application in marine engineering.

1 Introduction

With the growth of the world economy and the advancement of science and technology nowadays, the development and utilization of marine resources have become the focus of attention of all countries. Port terminals and bridges across the sea and submarine tunnels in coastal cities have become an important part of the development of infrastructure. However, due to the special characteristics of the marine environment with high chloride ion concentration, alternating humidity and heat, dry-wet cycle, strong corrosivity, and wind and wave impact, which makes traditional concrete easily eroded and impact in the marine environment, the marine engineering with concrete as the main material is facing serious durability problems, for example, the structure of the piers of cross-sea bridges in the role of the harsh marine environment, the efficiency of the damage to the concrete is significantly accelerated, which will affect the bridge The service life of the bridge structure will be affected.

Ultra-High Performance Concrete (UHPC) is widely used in marine engineering for its durability and corrosion resistance as well as excellent mechanical properties compared to traditional cement-based materials. UHPC has a dense internal structure and ultra-high

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mechanical properties, which effectively prevents structural collapse caused by external erosion and corrosion of reinforcing steel [1].

The purpose of this paper is to discuss the present state and anticipated future developments in the use of ultra-high performance concrete in marine environments. Firstly, this paper will describe the basic concept of UHPC, and analyze of its mechanism of action. This paper will also assess the current application of UHPC in marine engineering and discuss in depth the challenges faced by its application in the marine environment. On this basis, the paper will look forward to the development direction of UHPC in marine engineering. With the current advances in material science and construction technology, the innovation of UHPC materials in the research and development of new structures and the improvement of construction processes will further promote its wide application in marine engineering.

2 Basic concepts and characteristics of UHPC

Ultra-high performance concrete, whose basic components include high-strength steel fibers, superplasticizer, quartz sand, cement, and silica fume. It is a novel kind of fiber-reinforced cementitious material with high strength, high durability, high impact toughness, and has compressive strength greater than 120 Megapascals (MPa) and sustained postcracking tensile strength greater than 5.2 MPa [2]. It possesses excellent mechanical properties and superior durability. The ultra-high performance of UHPC is mainly obtained by improving the structure and properties of cement stone and the contact surface between cement stone and aggregate. Compared with traditional concrete materials, UHPC adopts the optimal granular grading of the constituent materials, the water-cement ratio is typically less than 0.25, and a high proportion of steel fiber materials are added, which can adapt to the freezing and thawing cycle, the marine environment, and the weak acid attack, and other harsh environments [2].

One of the properties of UHPC is its extremely low porosity, due to its optimized material mix and dense microstructure. The introduction of silica fume not only improves the densification of the material but also enhances the strength of the matrix through the volcanic ash reaction. In addition, the use of superplasticizers significantly improves the fluidity of the concrete, allowing UHPC to achieve a self-compacting effect during construction.

Secondly, its extremely low water-cement ratio and dense microstructure significantly reduce the permeability of moisture and harmful ions, making it excellent in resistance to chloride attack, sulfate attack, and carbonation. This property is particularly suitable for engineering applications in harsh conditions such as marine environments and chemical plants.

The excellent durability and crack resistance of UHPC is due to the incorporation of steel fibers. The three-dimensional network structure formed by the steel fibers in the concrete matrix effectively prevents crack propagation and enhances its ability to perform under dynamic loading. This gives UHPC a significant advantage in projects such as bridges, tunnels, and protective structures where high durability and safety are required. This property allows UHPC to excel when subjected to dynamic loading and extreme environmental conditions [3].

3 Mechanisms of action of UHPC in the marine environment

3.1 Specificity of the marine environment

In marine engineering, concrete materials face severe environmental challenges. The form of concrete erosion by the marine environment varies according to the location of the exposure zone, which can be divided into corrosion zones with different characteristics, such as marine atmospheric zones, marine splash zones, marine tidal zones, and marine underwater zones. Chemically, the marine splash zone and tidal zone are in the inorganic salt chemical corrosion environment, which is often the most serious area of erosion deterioration of concrete structures [4]. Firstly, chloride ions, which are abundant in seawater, can penetrate concrete and lead to corrosion of reinforcing steel; therefore, concrete materials must have very low permeability to resist chloride ion attack. In addition, the sulfates in seawater can react chemically with the cementitious components of concrete, causing the material to swell and crack, so concrete is required to have excellent sulfate resistance.

Physically, structures in marine engineering are often subjected to the impact of waves, tides, and floating objects, thus requiring high durability properties of concrete to extend the service life of the structure. Concrete also needs to have good crack resistance due to the dynamic loading and temperature variations in the marine environment. In cold marine environments at high latitudes, concrete structures may experience frequent freeze-thaw cycles, which are highly susceptible to material fatigue and damage. Concrete materials are therefore required to have high freeze-thaw resistance [5].

In summary, the marine environment places more stringent requirements on concrete, emphasizing the durability and erosion resistance of the material to ensure the long-term stability and safety of the structure.

3.2 Mechanism of action of UHPC in marine engineering

In the marine environment, the mechanism of action of ultra-high performance concrete is mainly reflected in its unique microstructure and material properties. UHPC forms a highly dense microstructure through optimized particle gradation and a low water-cement ratio. This structure significantly reduces porosity, which prevents the penetration of chloride ions and other hazardous substances and enhances the material's resistance to erosion [5]. The compactness and the UHPC matrix's strength enhance its chemical stability, which makes it perform well in sulfate and other chemically aggressive environments.

The steel fibers added to UHPC form a network structure in the concrete that significantly improves the toughness and crack resistance of the material. This enhancement enables UHPC to effectively prevent cracks from forming and expanding when subjected to complex physical loads, maintaining structural integrity. The low porosity and high densification of UHPC reduce the accumulation of moisture in the material, thereby reducing the damage caused by freeze-thaw cycles [6].

In summary, the mechanism of UHPC in the marine environment mainly relies on its dense microstructure, chemical stability, and enhanced mechanical properties, which together ensure its excellent durability and stability in harsh marine environments.

4 Current status of UHPC applications in the marine environment

In recent years, the application of ultra-high performance concrete in marine engineering has gradually increased, and domestic and international research and engineering practice have shown that UHPC has significant advantages in marine environmental engineering.

4.1 Status of domestic applications

The specific application of UHPC in cross-sea bridges mainly focuses on key parts such as bridge deck slabs, piers and connection nodes. China's Hong Kong-Zhuhai-Macao Bridge (HZMB) project is located in the Lingdingyang Sea, with high temperature, high humidity, high salinity of seawater, etc., impacted by the tides, dry-wet cycle, freeze-thaw cycle, salt spray, seawater, sea breezes and many other factors, the concrete structure of the corrosion of the harsh environment, the durability of the problem is very prominent [7]. Hong Kong-Zhuhai-Macao Bridge immersed tube tunnel along the basal soft soil thickness of about 30 meters, the bottom of the tube section of the longitudinal geological conditions are complex and uneven; top of the tube back to the silt and shipwrecks load, section joints force and waterproofing risk are high; The project is located in the outer sea, with complicated meteorological and hydrological circumstances, the project area of the daily average of more than 4,000 ships,intricate trajectory line, the safety of marine construction risk; giant immersed tube manufacturing crack-resistant impermeability risk is high (As shown in Figure 1); designed for 120 years of service life, the structural resistance of the structure is very high [8]. The service life is 120 years, which requires high structural durability. Instead, UHPC is widely used in bridge piers, bridge decks and key connecting parts, effectively resisting seawater and sea breeze environmental erosion and dry and wet cycles, effectively responding to structural durability problems (As shown in Figure 2), extending the service life of the bridge, and effectively lowering maintenance expenses [8][9].

Fig. 1. HZMB Segmental Bridge Box Girder Construction [8].

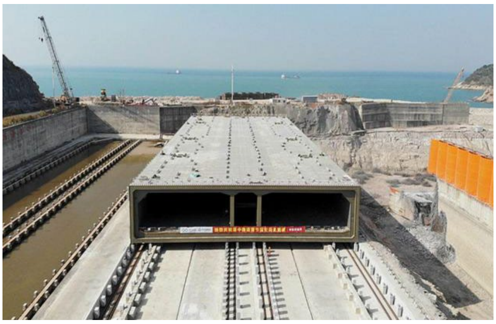

Fig. 2. HZMB Immersed Pipe Launching [9].

The application aspect of UHPC in offshore wind facilities improves the durability performance and wind load resistance of the structure. Unlike terrestrial installations, the construction of offshore wind farms is more susceptible to the effects of wind and waves brought about by climate change. Offshore wind foundations are subject to complex environmental loads, including wave impacts, tidal changes and wind loads, and UHPC's high strength and toughness enable it to effectively resist these loads. The Southern Power Grid Guishan Offshore Wind Farm is responsible for delivering green and clean wind energy to the Zhuhai power grid. It is the first offshore wind turbine in China to use an interpolated four-pile conduit frame foundation type. Due to the high number of typhoons in the sea area where the Southern Power Grid Guishan Wind Farm is located, high surge waves, ultra-high temperatures in the summer, and more cloudy and rainy weather, it puts forward ultra-high performance and technical requirements for the selection of concrete materials, grouting construction and management [10]. The use of UHPC as the foundation material for offshore wind power facilities significantly extends the service life of the wind power foundation (As shown in Figure 3).

Fig. 3. Southern Battery Guishan Offshore Wind Farm [11].

4.2 Status of foreign applications

The application of UHPC in harbor terminals has also achieved remarkable results. Seaport terminals need to withstand the erosion of seawater and mechanical loads. The Port of Hamburg is situated at the mouth of the Elbe River in Germany, which is significantly affected by tides and has frequent water level changes [10]. The harbor needs to withstand strong wave impacts from the North Sea and has high requirements for structural stability. Extreme weather events such as storms and sea level rise pose a threat to harbor facilities. And the salt in seawater is corrosive to concrete and steel structures, affecting structural durability (As shown in Figure 4). The Port of Hamburg utilized UHPC for the terminal upgrade. The low permeability and high-density internal structure of UHPC provide excellent resistance to corrosion and abrasion, as well as resistance to ocean current impact loads, freeze-thaw cycles, and extreme weather conditions faced by port terminals at high latitudes.

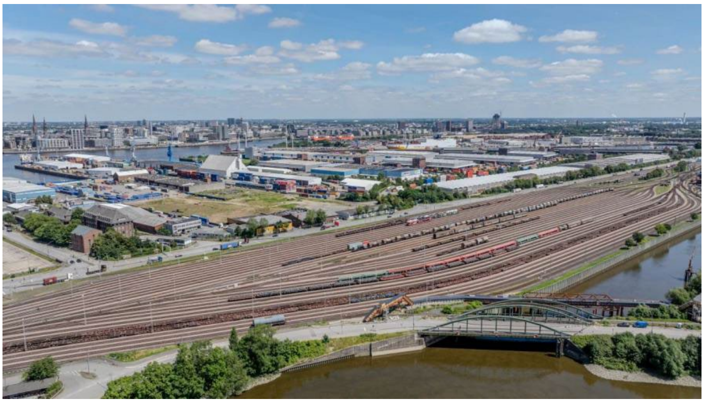

Fig. 4. Ship Transit and Land Transportation in the Port of Hamburg [12].

UHPC excels in breakwater applications. Breakwaters are constructed to protect port facilities and surrounding communities from marine hazards. Breakwaters need to withstand strong wave impacts, and UHPC's high strength and toughness enable it to effectively resist wave erosion. Japan's coastal areas are frequently affected by typhoons and tsunamis, and the strength and durability of breakwaters are required to be extremely high. After the 311 tsunami disaster in Japan, the Tohoku region was severely damaged and a breakwater rehabilitation project was carried out in Kamaishi Harbor, where UHPC was used in key structural parts of the breakwater, such as wave dissipation blocks and revetment panels [13]. Its high strength and mechanical properties ensure structural stability under extreme conditions, and UHPC is able to withstand strong wave impacts and extreme weather conditions. Its application ensures the reliability of breakwaters in all kinds of harsh environments (As shown in Figure 5).

Fig. 5. Condition of the top of the south dike at Kamaishi Harbor [13].

Offshore platforms are subject to complex environmental loads and chemical corrosion, and UHPC's high durability, low permeability, and excellent mechanical properties make it an ideal material choice. Norway's Troll A platform is one of the world's largest natural gas production platforms, located in the Norwegian North Sea, facing strong wave impacts, and complex environmental loads, and need to resist seawater corrosion and high-latitude offshore projects face relatively frequent freeze-thaw cycles and extreme weather conditions [14]. The use of UHPC in key structural joints to enhance the durability and stability of the platform has significantly improved its safety and service life (As shown in Figure 6).

Fig. 6. Troll A offshore gas production platform in Norway [15].

The application of UHPC in marine engineering is promising, and its outstanding mechanical properties and durability make it an ideal material choice for marine engineering. Future research should further optimize the mix ratio design and construction process of UHPC to give full play to its potential in ocean engineering.

5 Challenges to the use of UHPC in marine engineering applications

The primary challenge facing the application of UHPC in marine engineering is cost-effective. The high cost of raw materials for UHPC, especially the use of high-strength cement, silica fume and steel fibers, makes its manufacturing cost significantly higher than the conventional concrete materials. In addition, the construction process of ultra-high performance concrete is relatively complex and requires high levels of construction equipment and technicians, which may lead to lower construction efficiency and thus increase overall project costs [16].

The production and application of UHPC also involves issues of environmental impact. The production process of high-strength cement generates large amounts of carbon dioxide emissions, which can place additional burdens on the environment. Therefore, when promoting the application of UHPC, it is necessary to consider how to reduce its carbon footprint and develop more environmentally friendly production processes and material substitutions to minimize the adverse effects on the environment [17].

For now, the application of UHPC in marine engineering also faces the problem of a lack of management norms and standards. Since UHPC is a relatively new material, many countries have not yet established perfect technical standards and construction norms. This reveals that in practical application, the design and construction may lack uniform guidance, affecting the quality and safety of the project. Therefore, the development and improvement of UHPC-related management norms and standards is the key to promoting its wide application in marine engineering [18].

It can be seen that although UHPC has significant application potential in offshore engineering, its promotion and application still need to overcome various challenges such as cost, productivity, environmental impact and, management standardization.

6 Conclusion

As material science and construction technologies continue to advance and grow, the application of UHPC in the marine environment is promising. First of all, UHPC shows excellent mechanical properties, durability and impermeability in the marine environment, which makes it an ideal cementitious composite material suitable for harsh marine conditions. The application of UHPC can significantly enhance the safety and durability of offshore constructions., and its excellent performance can help extend the service life of the structure and lower the cost of long-term maintenance. UHPC is also particularly suitable for the protection of UHPC is also particularly well suited to protect the functionality of critical parts of offshore structures, such as breakwaters, offshore platforms and port facilities, which require high material performance due to their functional importance, high utilization and cost.

Through in-depth research and application promotion of UHPC in the marine environment, it can not only improve the safety and durability of marine engineering but also provide support for sustainable development and green construction. Since this paper is mainly based on a literature review and lacks specific data and experimental verification, further research and exploration are still needed in practical application. How to stimulate the potential of this material to make it more suitable for different complex marine environments requires deeper and more specific research.

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