Application of High-Performance Concrete in Bridge Structures Under Extreme Environment

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Abstract. Bridges in extreme environments combine the mission of connecting remote areas with the challenge of surviving in harsh environments. For the high quality construction and long term application of bridges, the design and application of high-performance concrete (HPC) are researched in this paper. Firstly, the application of HPC in bridges under cold environment is studied. Based on the failure mechanism of concrete and mix ratio design of HPC in cold area, the conclusion is drawn that adding appropriate amount of diatomaceous earth materials can better adapt to cold environment. Then, what kind of HPC is suitable for bridge in coastal environment is explored. By studying the failure mechanism and mix ratio of concrete in coastal areas, it is found that adding the appropriate amount of blast-furnace slag (GGBS) can better resist the damage caused by the ocean. Finally, the working condition of HPC is defined as the construction of bridges in hot environment. The HPC was designed after consulting the difficulties of concrete pouring in hot weather. The experimental results show that adding a proper amount of fly ash can solve this problem. This study can provide a reference for using HPC to build bridges in different extreme environments.

Keywords: High-performance concrete; bridge structure; extreme environment.

1. Introduction

With the gradual improvement of the national traffic lines, the construction of bridge projects in China has gradually entered a stable period, and the requirements of people for the service life of bridges are increasing. China has a vast territory, and there are many bridges applied in extreme environments. The harsh environment has more obvious impact on bridges. On the one hand, the existing bridges have been damaged to varying degrees, which cannot reach their expected service life, such as the low frost resistance durability of concrete bridge structures in severe cold areas, and the weak corrosion resistance in coastal areas. On the other hand, bridge construction is difficult, such as poor crack resistance of concrete bridges in hot environments.

High-performance concrete (HPC), a new type of concrete, is made of high-quality raw materials with modern concrete technology. It is a mix of cement, aggregates, water and sufficient high-quality mineral admixtures and efficient admixtures according to a suitable water-cement ratio. The concrete is characteristic of high strength, durability, good pumpability and high permeability resistance [1, 2]. Therefore, the research on HPC has become one of the hot topics in the field of civil engineering and its rapid development provides favorable support for the construction and development of bridges. At the same time, many scholars are studying the design of mineral admixtures and mixtures in different extreme environments, so as to better solve problems according to local conditions and improve the durability of bridges.

Since the research and application of HPC has become a hot spot to solve the problem of bridge, it has been widely used all over the world, especially in developed countries. For example, the deck of a low permeability HPC floating bridge is constructed in Seattle, USA, and the underwater foundation of the Akashi Channel Bridge, which connects Honshu and Shikoku in Japan, is made of

HPC [3, 4]. Compared with other countries, the development of HPC in China started relatively late, and it is mostly applied in economically developed areas. However, the role of bridges is even more important in harsh environments, where high-quality materials are needed to improve bridge life. It can be seen that there is still a long way to go before HPC is promoted nationwide.

Aiming at cold, coastal and hot environments, this paper proposes the main reasons for concrete damage caused by these three extreme environments, respectively. Then, suitable mixture ratio of HPC is designed according to different environmental damage mechanism. Finally, whether it can enhance the durability of bridge engineering is verified.

2. Application of HPC in Bridges under Cold Environment

2.1. Failure Mechanism of Concrete

In the cold region, due to the extreme cold environment and temperature changes, the structure of concrete is severely tested from the natural environment. It contains the main beam by freezing caused by concrete spalling, corrosion of reinforcement to produce cracks along the reinforcement, pile foundation by freezing, scouring caused by broken piles and other durability disasters.

Freeze-thaw damage is the main form of damage, the reason is that in the cold regions easily meet the two main conditions for the occurrence of freeze-thaw: (1) Concrete has water infiltration, so that it is in high saturation. (2) The existence of alternating positive and negative temperature changes [5-7].

2.2. Mix Ratio Design and Performance Test

The research shows that the concrete can be mixed with silica-based materials to improve its frost resistance, which can improve the pore structure inside the concrete. The incorporation of diatomaceous earth has a refining effect on the pore structure of concrete, reducing the internal coarse pores, effectively increasing the fine pores, increasing the porosity of the slurry, reducing the pore size, and shortening the permeation path of unfrozen water. At the same time, the admixture of diatomaceous earth can make the hydration reaction of cement more complete, which makes the concrete structure more dense and stronger. The results show that the freezing resistance of concrete can be judged by the degree of freezing damage of concrete. As shown in Table 1, the freezing resistance of C40 concrete mixed with 1% diatomite is 29% higher than that of ordinary concrete and the anticoagulant performance of C30 concrete with 1.5% diatom content is improved by 37% [5].

Table 1. Antifreeze capacity of three kinds of concrete [5]

Lable	C50		C40		C30	
Mix Proportion	Ordinary	Diatomite 1.5%	Ordinary	Diatomite 1%	Ordinary	Diatomite 1.5%
Antifreeze Capacity	0.49	1.25	1.94	1.38	4.29	2.7

2.3. Preliminary Conclusion

Therefore, admixture of appropriate number of diatomaceous materials in concrete can improve the internal structure and catalytic reaction effect. By improving the internal structure, the unfrozen water penetration path can be shortened and the hydrostatic pressure of concrete can be reduced. The catalytic hydration reaction can promote the formation of C-H crystalline nuclei and reduce the orientation of Ca (OH)2 crystals on the aggregate surface, resulting in a denser concrete. Overall, the incorporation of appropriate amount of diatom material is beneficial to improve the frost resistance of concrete and better adapt to the severe cold environment.

3. Application of HPC in Bridges under Coastal Environment

3.1. Failure Mechanism of Concrete

Due to the service environment and material characteristics of the concrete structure of the coastal bridge, the concrete structure is subjected to more severe natural environment test than that of the inland. Coastal engineering not only be eroded by high concentration of corrosive ions in seawater, but also the effect of tides and waves that lead to the alternations of wet and dry concrete surface significantly reduce the life of engineering structures over time.

There are four main damage mechanisms of concrete in coastal areas.

(1) The first is the carbonization mechanism. $Ca(OH)_2$ produced in the hydration process of cement and CO_2 produced by decomposition of microorganisms in the atmosphere or ocean generate $CaCO_3$ and H_2O. This chemical reaction reduces the PH value, and then the basic protection of the concrete against the reinforcement gradually disappears [8].

(2) The second is the chloride ion corrosion mechanism. When chloride ions penetrate into the reinforcement surface, the local protective film with high chloride ion concentration is destroyed and becomes an activated state. Under the condition of sufficient oxygen and water, the activated steel bar surface forms a small anode, the non-activated steel bar surface becomes the cathode, and the anode metal iron dissolves, forming a corrosion pit [8].

(3) The third is the sulfate attack mechanism. Sulfate reacts with some components of set cement to form expansion products such as ettringite and gypsum, resulting in concrete expansion, cracking, spalling and disintegration [8].

(4) The fourth is the mechanism of seawater erosion. It is caused by many reasons, including the erosion of seawater components, the erosion of microorganisms in seawater, the mechanical collision of floating objects, etc., showing the interaction of various corrosion components [8].

3.2. HPC Mix Ratio Design and Performance Test

The corrosion of steel bar caused by chloride ion and carbon dioxide infiltration into concrete is the main reason which affects the durability of bridge in marine environment. In order to achieve the low permeability of concrete, the water-binder ratio should not be greater than 0.4 [8]. The water consumption and water-binder ratio can be significantly reduced by adding high-potency water reducer. The addition of ground granulated blast-furnace slag (GGBS) results in reduced pore connectivity in concrete [9]. As shown in Table 2, a large amount of GGBS is added to prepare HPC, as well as corrosion inhibitor which can improve the early strength of HPC [10].

Table 2. Concrete Test Match Ratio and Performance of Mixture [10]

Specimen ID		XP350	XG351	XG501
Strength grade		C35	C35	C50
Mixing amount of cementitious material / %		90C+10F	55C+10F+30S+5R	
Sand coarse aggregate ratio / %		37	37	38
Water-binder ratio		0.40	0.40	0.33
Raw material / (kg/m^3)	Cement	356	217	250
	Fly ash	40	40	45
	GGBS	0	119	136
	Sand	700	698	698
	Rocklet	450	449	447
	Rock	676	673	670
	Water reducer	158	158	150
	Corrosion inhibitor	-	20	23
Slumps / mm		195	215	205
Gas content / %		4.4	4.0	4.1

*Note: C is for cement, F is for fly ash, S is for GGBS, R is for corrosion inhibitor, P is for normal concrete, and G is for HPC.

Durability tests such as impermeability test, carbonation test and chloride ion erosion test were carried out on the HPC as compared with ordinary concrete. The durability of HPC was obviously enhanced [10].

3.3. Preliminary Conclusion

Two conclusions have been drawn from the results of the experiment. One is that the compressive strength of concrete decreases with the increase of water-binder ratio. The other is anti-seepage, anti-corrosive media erosion ability of the HPC has been significantly enhanced. Therefore, the preparation of HPC in coastal areas should be mixed with high efficiency water reducer to reduce the water-binder ratio of concrete and slag powder to improve the pore structure of concrete. These two methods can improve the concrete compactness, thus improving the durability of bridge structure.

4. Application of HPC in Bridges under Hot Environment

4.1. Failure Mechanism of Concrete

In hot areas, the construction difficulties mainly come from two aspects. The process requires that the construction time should not exceed 24 hours and continuous construction should be carried out without interruption. The conventional method cannot be used to stagger the pouring of concrete during the high temperature period. Therefore, the corresponding technology must be used in the construction to ensure the construction quality, and promote the smooth completion of slip form operation. Because the construction project is located in a hot area and the climate is relatively dry, the initial setting time of concrete is relatively short, which is difficult to control effectively [11].

4.2. HPC Mix Ratio Design and Performance Test

Adding fly ash into concrete has great influence on workability and pumpability of concrete [12]. As shown in Table 3, by greatly adjusting the content of cement and fly ash in concrete, the hydration rate and heat of hydration of cement can be reduced and the water reduction effect of fly ash added in a certain proportion can be fully utilized. The water-binder ratio of concrete is further reduced to ensure the retarding performance of concrete. The early strength of concrete also meets the requirements of normal construction, so that the harm caused by summer construction is minimized and alleviated from the internal causes of concrete. At the same time, measures such as reducing the temperature of raw materials, reducing the heat absorption of concrete during mixing and transportation, and strengthening the curing of concrete have successfully solved the hot problem.

Table 3. Concrete Mix Proportion [11]

Mix proportion No.	Mix proportion / %	Mix proportion material consumption							Water binder ratio
		Cement	Fly ash	Mineral powder	Sand	Crushed stone	Water	Water reducing agent	
1-1	50	192	192	0	737	1152	127	3.46	0.33
1-2		192	192	0	735	1150	131	3.46	0.34
1-3		192	192	0	734	1148	134	3.26	0.35
2-2	55	173	212	0	717	1171	127	3.46	0.33
2-2		173	212	0	735	1149	131	3.27	0.34
2-3		173	212	0	752	1128	135	3.27	0.35
2-1	70	115	270	0	717	1171	127	3.27	0.33
3-2		115	270	0	735	1149	131	3.27	0.34
3-3		115	270	0	752	1128	135	3.08	0.35
4-1	24	251	91	38	751	1175	144	3.80	0.38

4.3. Preliminary Conclusion

Due to the typical characteristics of large fly ash content and low cement content, high fly ash and high-performance concrete greatly reduce the hydration rate and temperature gradient of concrete. Thus, the situations such as the summer construction of concrete slump loss is too large and fast, and the solidification and hardening are too fast, can be avoid effectively. Therefore, adding fly ash to a certain extent can improve the working performance of concrete and solve the problem of bridge construction in hot areas.

5. Conclusion

This paper examines different extreme environmental conditions by researching how to improve the performance and durability of HPC under different extreme environmental conditions. The following main conclusions are obtained.

(1) In cold areas, the addition of diatom can improve and catalyze the internal structure and reaction effect of concrete, and reduce the influent pressure of concrete. As a result, the freezing resistance of concrete is significantly improved and it is more suitable for cold environment.

(2) In coastal areas, HPC is mixed with high efficiency water reducing agent, which reduces the water-cement ratio between concrete and GGBS, and improves the internal structure of concrete. At the same time, the compactness of concrete mix ratio and durability of bridge structure have been significantly improved.

(3) In hot areas, by adding a large amount of fly ash to HPC, the hydration rate and temperature gradient of the concrete are reduced, and the operational performance of the concrete is improved, so that it can better work in high temperature environment.

In summary, the research demonstrates that the use of HPC improves various performances of the structure. In contrast, using different mix designs provides solutions to targeted problems. Firstly, the addition of diatomaceous earth material can improve the frost resistance. Secondly, the addition of GGBS improves the impermeability. Thirdly, the addition of fly ash improves the retarding performance. Therefore, HPC can be formulated with different materials in different extreme environments to optimize the use of bridges following local conditions. This paper focuses on the advantages of HPC over ordinary concrete, but does not compare its economic benefits. It explores the function of specific admixtures, but does not carry out more tests on their proportions to select the best admixtures. In the future, it would be beneficial to further investigate the known results to support the widespread use of HPC.

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