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Design and durability analysis of marine concrete

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Abstract. Marine engineering is an important way for a country to go deep blue. In the marine environment, there are many factors that affect the durability of concrete, among which the most harmful one is chloride ion erosion. In order to improve the ability to resist chloride ion permeation, this paper designs, compares and selects the appropriate water cement ratio of marine concrete, with the use of new anticorrosive technologies such as epoxy coating and silane impregnation. The design service life and the chloride ion diffusion coefficient prediction are analysed by establishing models, and this paper verifies whether the engineering design meets the service life requirement.

1. Introduction

In offshore engineering, concrete in marine environment works in a very complex environment. It is affected by many erosion factors, the most common failure modes that affect the durability of concrete are carbonization, salts erosion dominated by chloride ion erosion, freeze-thaw cycle and alkali aggregate reaction. Under the influence of the actual marine environment, the corrosion of steel bar caused by chloride ion erosion is the main factor leading to the deterioration of concrete performance, chloride ion in the ocean is mainly transported by concentration gradient.

Project A is the pile foundation part of the operation of offshore bridge interconnection project. The project is located in the underwater environment of marine environment, about 1km from the coast. The construction environment in this area is harsh and the currents are turbulent. The annual average free chlorine ion content of seawater is about 13000 mg/L[1], the sea water density is 1.025 g/cm^3. Under the marine environment, the existence of carbon dioxide, oxygen, pH value and salts such as chloride ion will lead to the destruction of concrete structure and reduce the durability of concrete. At the same time, the navigation density of the area is large, ships will be more intensive during the fishing season, the concrete structure may be worn and impacted.

2. Durability design of concrete

2.1 Design service life of concrete structure

Project A of the Bridge engineering is an important link between the island and the interior, it is also an important node for the expressway network to communicate between the island and the inland. The project will greatly improve the efficiency of the personnel and logistics from the island to the inland,

and greatly promote the development of the economic and cultural undertakings, such as tourism, commodity transportation and so on. The service environment is underwater area of marine chloride environment, and the surrounding area is permanently immersed in seawater. The environmental effect level is III-C according to the Code for Durability Design of Concrete Structures. The design service life of the project is 100 years.

2.2 Design and selection of marine concrete

According to the Technical Code for Anticorrosion of Concrete Structures in Seaport Engineering, as the concrete for pile foundation used in marine environment: the lowest concrete strength grade is C25, the maximum water cement ratio is 0.50, and the minimum concrete cement consumption is 300 kg/m^3. The marine concrete grade selected for this project is C35 because of the service environment. In order to obtain stronger resistance to chloride ion permeation, a large number of fly ash and mineral powder will be added to marine concrete to replace cement. One of the main reasons is to optimize the pore structure of concrete. Increasing compactedness will fundamentally prevent chloride permeation and improve the ability of marine concrete to resist chloride ion erosion. Table 1 gives the details of the mix design.

Table 1 Design table for marine concrete mix design (unit: kg/m^3)

Number	W/B	Cement	Fly ash	Slag powder	Sand	Stone	Water	Admixture	Rust inhibitor
1	0.37	156	117	117	859	1008	144	3.50	/
2	0.35	164	123	123	831	1015	144	3.69	/
3	0.33	175	131	131	801	1019	144	3.93	/

According to the mixture ratio of Table 1, the measured results are shown in Table 2.

Table 2 Measured results of concrete mix test

Number	Density (kg/m$^{3)}$	Slump (mm)	R7 Compressive strength (Mpa)	R28 Compressive strength (Mpa)	84 days Chloride ion diffusion coefficient (1×10^{-12} m^2/s)
1	2390	219	32.2	43.5	1.05
2	2400	220	36.3	47.8	1.00
3	2400	220	40.8	52.9	0.94

The project needs the slump in (200 ± 20) mm range, the minimum design strength of concrete is 35 Mpa and the trial-mix strength is 43.2 Mpa, the 84 days maximum chloride ion diffusion coefficient is 1.01×10^{-12} m^2/s.

According to Table 2, all tests meet the slump requirements, they are basically the same and greater than 160mm, which belongs to the large fluidity concrete. According to 7 days (the 7 days compressive strength is set to meet the requirements of abnormal working conditions, such as rush period and so on) and 28 days compressive strength results, only test 2 and 3 can meet the requirements. From the 84 days chloride ion diffusion coefficient results, test 2 and 3 meet the requirements of specification.

The most important thing in this project is the ability to resist chloride ion erosion, test 2 and 3 meet the requirements of specification, they have strong resistance to chloride ion permeation. Test 1 is abandoned because of its poor resistance to permeation and poor strength. For test 2 and 3, the use of cement, slag powder and fly ash in test 3 is even greater. Economically speaking, the cost of adopting ratio 3 will be much greater than the cost of adopting the ratio 2 in large area construction. In conclusion, the project selects the ratio 2 to produce concrete.

2.3 Selection of anticorrosion measures

In order to enhance the durability of concrete, the main anticorrosive measures such as epoxy resin coated steel bar and silane impregnation are adopted in the project.

Epoxy coated steel bar refers to the coating of steel bar coated with epoxy resin powder by electrostatic spraying in the factory. Epoxy resin coat can prevent the contact between steel bars and external substances, then it will prevent electrochemical corrosion and surface chemical reaction of steel bars. In addition, epoxy resin coating itself does not react with acids or bases, it can be applied to concrete alkaline environment for a long time, and has strong corrosion resistance and wide applicability. The epoxy resin coating is used in steel bars of pier body, bearing platform and so on below the elevation below +7.00 m. The schematic diagram of the main pier bearing platform is shown in Figure 1.

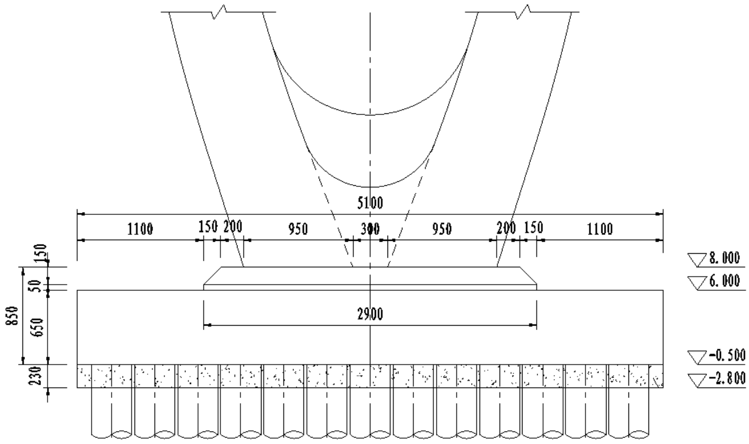

Figure. 1 Schematic diagram of main pier bearing platform

Silane impregnation is a process of spraying concrete structure surface with silane compounds. The principle is to use silicane to impregnate the small molecular characteristics of the coating, penetrate the concrete capillary wall deeply, and form a firm integration on the concrete surface. This will greatly prevent the corrosion of concrete and effectively protect the concrete structure. The silane impregnation will be compared with the conventional coating method, as shown in Table 3.

Table 3 Comparison table between silane impregnation and conventional coating method

Processing mode	Service life	Construction difficulty	Construction time	Quality Control	Construction cost
Silane impregnation	15-20 years or more	Simple base treatment, spraying and brushing	Very short, skilled workers can brush more than 10000 m^2 per day.	Easy control, and the construction staff can be built by simple training, and the quality can be guaranteed.	Low cost, and it can be reduced 5-6 times in the design service period
Conventional coating method	Usually 5-10 years.	Complex and difficult	Very long, Skilled workers can brush about 1000 m^2 per day.	Requires environmental, personnel and material guarantee.	The cost of raw materials is high and construction costs are higher.

2.4 Determination of other design parameters
According to the environmental effect level and service environment, the Code for Durability Design of Concrete Structures stipulates the minimum thickness of concrete cover is 50mm, which can increase 10 to 20mm in the flowing seawater or in the sediment eroded by water. For the reinforced concrete structure with grade C, the allowable value of the surface crack width is 0.20. The Technical Code for Anticorrosion of Concrete Structures in Seaport Engineering stipulates the maximum crack width of the underwater area is 0.3mm, and the minimum thickness of concrete cover is 30mm. Project A follows the two specifications clearly confirms: the thickness of concrete cover is 70 to 75mm based on the specific environment; the allowable value of the surface crack width is 0.20 and the maximum crack width is 0.2mm.

2.5 Analysis of concrete durability design
In order to analysis the design of concrete structure, this section adopts the Japanese JSCE standard concrete durability analysis model to analysis the service life of concrete design, the model using the following equation:

$$\gamma_i \gamma_{cl} c_{ca} \left(1 - erf \frac{x}{2\sqrt{\gamma_c t D_{RCM,0}}} \right) \le c_{cr} \tag{1}$$

where γ_{i} is the structural importance coefficient; γ_{cl} is the variation coefficient of chloride concentration on bar surface; c_{ca} is the chloride ion concentration on concrete surface; γ_{c} is the variation coefficient of concrete material performance; *x* is the concrete cover thickness; c_{cr} is the critical chloride ion concentration of concrete; $D_{RCM,0}$ is the chloride ion diffusion coefficient; *t* is the design service life.

Using the Japanese JSCE standard concrete durability analysis model to analysis the project, it is found that the design service life of the concrete structure is directly proportional to the square value of the thickness of concrete cover. With the increase of the thickness of the concrete cover, the growth rate of the design service life is getting larger and larger. The result is shown in Figure 2.

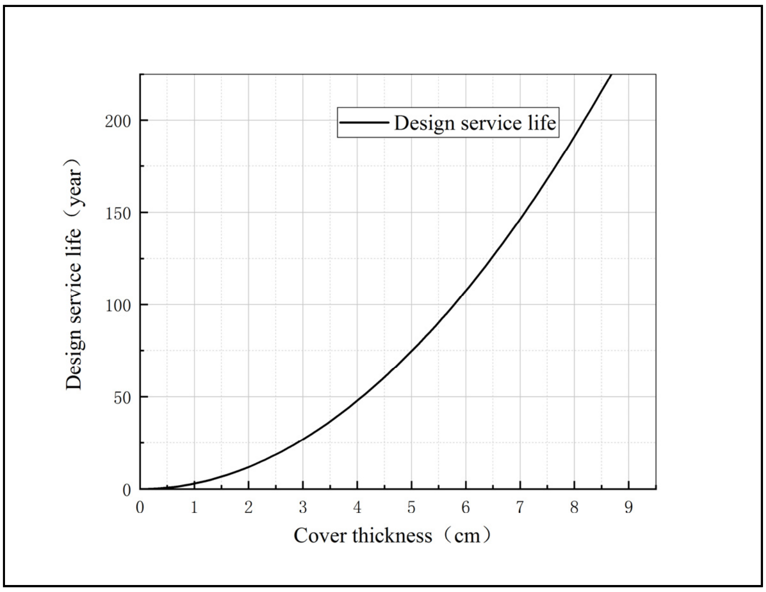

Figure. 2 Analysis diagram of concrete durability

In this project, the thickness of the concrete cover is in the range of 7 to 7.5cm. According to this, the design service life is analysisd and Figure. 3 shows the details.

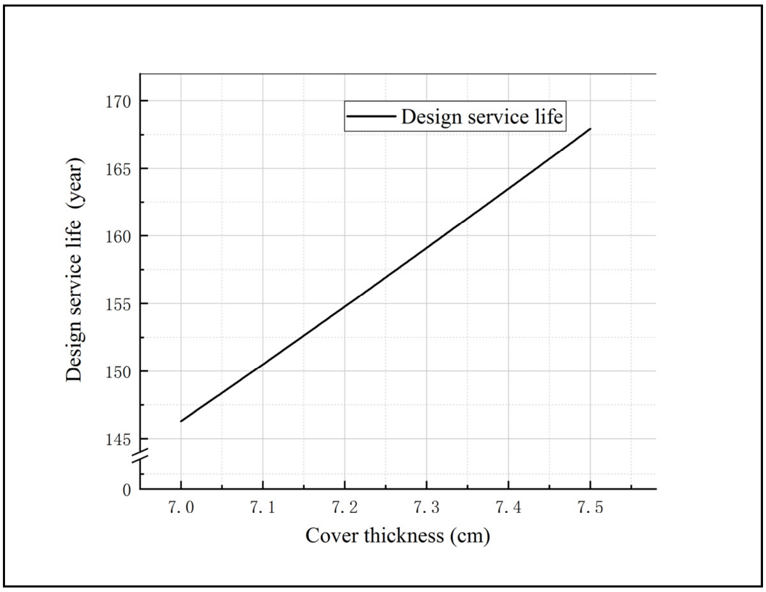

Figure. 3 Analysis diagram of the design cover thickness

According to Figure. 2, the design service life is between 146 and 168 years in the design thickness range, which meet the 100 year service life requirement of major projects. However, there is a limitation in the JSCE standard design and analysis model. It gives the definition of chloride ion diffusion coefficient is constant and does not vary with time.

In order to explore the relationship between chloride ion diffusion coefficient and time variation, according to the existing research efforts[2,3,4], the chloride ion diffusion coefficient time-varying model is modeled, it can be described as follows:

$$D(\mathrm{t}) = D_0\left(\frac{t_0}{t+t_0}\right)^m \tag{2}$$

where m is the time empirical coefficient; t_0 is the concrete curing age; t is the exposure time; D_0 is the diffusion coefficient of reference period (generally 28 days).

Shi Jiale[5] proposed a chloride ion diffusion coefficient time-varying model under different chloride environments, and it is shown as follows:

$$D(\mathrm{t},T)=\mathrm{k}\left[A_1\left(r^2\right)+B_1\left(r\right)+C_1\right]\left(\frac{28}{28+t}\right)^{A_2(r)^2+B_2(r)+C_2} \tag{3}$$

where $D(t,T)$ is the chloride ion diffusion coefficient; k is the time-varying model parameters; r is water cement ratio; A_1, B_1, C_1, A_2, B_2, C_2 are simulation coefficients.

Based on the above two models, the results are shown in Figure. 4. The results show that the chloride ion diffusion coefficient decrese with growth of time, and this decrease presents a trend of decreasing fast in the early stage and decreasing slow in the later stage. Based on the construction experience, the chloride ion diffusivity coefficient decreases with growth of time is due to the use of large quantity fly ash and slag powder. It correlate well with simulation. The two models differ in the simulation results, probably due to the difference between the actual environmental parameters and the empirical coefficient. But the two simulation curves have the same trend and their results are very close. The two models can be used for analysing concrete durability.

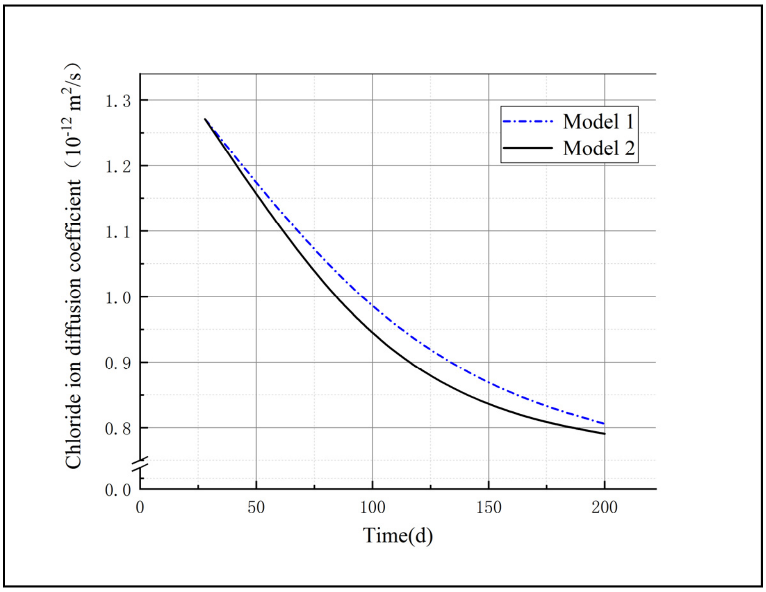

Figure. 4 Analysis diagram of the two time-varying model

3. Conclusion

（1）Project A belongs to major engineering grade, it works in marine chlorides environment, and its environmental effects level is III-C. The design service life of the project is 100 years. Epoxy resin coated steel bars and silane impregnation processes are used to protect the concrete structure.

（2）The pile foundation of project A uses the strength grade C35 and the water cement ratio of 0.35 marine concrete. The mix proportion is cement: fly ash: slag powder: sand: stone: water: admixture =164:123:123:831:1015:144:3.69. The strength of concrete, resistance to chloride ion permeation and collapse degree meet the engineering requirements.

（3）By using the Japanese JSCE standard concrete durability analysis model, the service life of the designed concrete structure is estimated to be between 146 and 168 years. It is easy to get the inverse ratio between the chloride ion diffusion coefficient and the design service life. In order to further improve the concrete durability analysis model, two chloride diffusion time-varying models are used to derive the law of chloride diffusion coefficient decreases with time growth. Using the law, the decrease of chloride ion diffusion coefficient will inevitably increase the design service life. At the same time, considering the use of a series of auxiliary anticorrosion measures mentioned above, the concrete actual service life can meet the design requirement of 100 years. The analysis of the durability of concrete structure can be combined with the above models to make a reasonable prediction of the design service life, and provide guidance for production practice.

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