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Durability zonation standard of concrete structure design

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Abstract: Durability zonation standard (DZS) is proposed to provide useful parameters for durable concrete structure design. It deals not only with the influence of environment on structures, but also with types, functions and importance of structures based on the theory of life cycle cost(LCC). First, the basic concept of DZS for concrete structure design is defined. Then the basic principles for DZS are established. The factors for zonation according to natural environmental conditions and structural importance are identified. The usefulness of DZS by citing a real application for concrete highway bridges in Zhejiang Province is demonstrated. Finally, durability regulations are provided accordingly to zonation.

Key words: durability zonation standard; concrete structure design; zonation map; life cycle cost

Durable concrete structure design should deal not only with the influence of environment on the structures, but also with the types, functions and importance of them based on the theory of life cycle cost (LCC). It is important to obtain the useful parameters of durability designs effectively. To date, different working environmental classifications have been introduced into some durability design specifications and standards, which are all based on the erosion degree of the environmental conditions. These specifications and standards include "Code for design of concrete structures" (GB 50010—2002)[1], "Code for anticorrosion design of industrial constructions" (GB 50046—95)[2], "Guide to durability design and construction of concrete structures"[3] and CEB/FIP "Durable concrete structure design guide"[4], etc. However, they have only considered some regulations about materials and conformations corresponding to their classifications instead of quantifying the requirements for durability and service life directly. So it is necessary to establish a general rule to help judge the environment for durable concrete structures by analyzing multi-environmental factors. Such a rule can serve as the first step in making a rational durability design method possible. It is, therefore, essential to specify a zonation for concrete structure durability design.

1 Basic Concept of DZS

The durability zonation standard (DZS) is a global and comprehensive rule for concrete-structural design. It deals with both the environment around the structure and the degree of environmental influences on concrete structure durability. The durability zonation (DZ) is the focal point of the whole content of DZS.

Globally, DZ divides the map of the object area into several regions on the basis of environmental conditions and the importance degree of each region. The environmental conditions of each region determine the degrees of concrete carbonization, chloride erosion, reinforcing bar corrosion, freeze-thaw cycles, etc. The characteristic parameters for concrete structure durability, such as temperature, humidity, the density of CO_2, Cl^- and O_2 should be taken into account while determining the environmental conditions. Some rules[1-4] have identified those environmental classifications. Obviously, the atmospheric environments and the coastal/oceanic environments are two basic environmental types. The importance degree of each region concerns the economic losses and the political influence due to the durability invalidation of concrete structures. This mainly depends on the degree of the region's development.

Locally, some factors of the structures, such as the locations, the types and the functions of them should be considered in DZS. Some other characteristic parameters may be considered in the coefficients of DZS as well.

DZS can help ease the concrete structure durability design. It can lead to a rational design method for concrete structure durability similar to the aseismic zonation standard which is attached to "Code for seismic design of buildings" (GB 50011—2001)[5].

2 Principles of DZS

1) DZS should represent the asymmetric space-

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time distribution of the durability degradation of concrete structures according to natural environmental conditions such as hydrological, climatic and geographic conditions.

The phenomenon called as "freeze in north and rust in south" exists in the concrete structures all over China caused by climatic and geographic conditions. The severe coldness of North China usually causes freeze-thaw destruction and salt-freeze destruction of concrete structures, while humidity, torridity and oceanic ambience of South China cause corrosion of reinforcing bar by concrete carbonization and/or chloride erosion. In such a southeast coastal province as Zhejiang, the durability degradation degree evidently decreases with the transformation from sea to land and from south to north.

Besides space, durability degradation is also affected by time. The corrosion of the reinforcing bar in concrete is a typical accumulative progress over time.

Therefore, a unified durability environmental zonation standard should be established combining the distribution of natural conditions with the durability degradation progresses of structures in order to ameliorate the theories of durable structure design and durability assessment.

2) DZS should consider not only the influence of the environment level but also that of the material level, the component level and the structure level.

Research on durable concrete structures can be classified into four levels, including the environment level, the material level, the component level and the structure level, which involves two aspects: durable structure design and durability assessment with service life prediction.

DZS shuold be founded on the basis of research results on the environmental level, synthesizing results on the other levels at the same time. And suitable parameters for zonation should be identified by comprehensive analyses of environmental factors and actions.

3) DZS should take full advantage of the existing design principles and optimize the structural life cycle cost (SLCC) by taking account of structural types, functions, importance and economic factors.

It should be the developing trend that the structural member design be replaced by the structural frame design based on the performance-based design theory following the principles of SLCC. Research results on durability and current structural design principles should be unified to put forward the optimum performance-based design theory for durable structure with rational design instead of qualitative analyses. DZS, as a part of the design theory, should be confirmed by comprehensive analyses according to environment, structural function, type and importance, etc.

3 Factors for Durability Zonation

3.1 Selection of the environmental factors

DZ can be defined with two groups of factors as follows:

1) Influence factors of environmental climate

These factors, including air temperature, humidity and precipitation, etc., are connected with the concrete depression produced by the freeze-thaw cycles and steel bar corrosion produced by the carbonation of concrete, chloride ingress, propagation of corrosion, etc.

2) Influence factors of environmental erosion

Chloride content is mainly concerned about coastal/oceanic, salt-lake and deicing-salt environments. The effects of sulfate and magnesium existing in soil should also be taken into account.

Useful factors for DZ can be selected from the factors mentioned above according to the environmental conditions.

Atmospheric environment and coastal/oceanic environment are chosen as the focal objects. None of freeze-thaw, salt-freeze, saline-crystallization, polluted-atmospheric or chemical-corrosive environments is to be discussed emphatically here. Discussion of them will be put into articles in future.

1) Atmospheric environment

The main factors of this kind of environment are humidity, temperature and the supply of CO_2 and O_2.

2) Coastal/oceanic environment

Chlorine diffusion coefficient and surface chloride content determine chlorine erosion together. There are many factors influencing chloride diffusion coefficient, among which temperature and humidity are two main factors of natural conditions. As to surface chloride content, besides chloride content in the surface layer of sea water, the height above the sea level is the decisive factor in oceanic environment[3,6], while the distance from coast and wind (direction, force and speed) are the decisive factors in coastal environment.

3.2 Analyses of environmental factors

Zhejiang Province is selected as an example for analysis. The natural conditions of Zhejiang are introduced before the analysis as follows:

Zhejiang lies in the southeast coastal area of China, belonging to the typical subtropical monsoon-climate area. It has a long coastline and numerous islands, including seven cities which are Taizhou, Wenzhou, Zhoushan, Ningbo, Shaoxing, Jiaxing and Hangzhou, and a total of 38 counties.

The major characteristics of the climate in Zhejiang are: remarkable monsoon season, clear distinctions between the four seasons, moderate annual temperature, much sunlight, plentiful rainfall, humid atmosphere and a rainy season in synchronism with the hot season. The mean annual temperature is 16.9 ℃, with the highest being 33.4 ℃ and the lowest −2.2 to −17.4 ℃. The annual rainfall varies from 980 mm to 2 000 mm. Influenced by the monsoon of East Asia, the prevailing wind direction in summer is remarkably different from that in winter. And there is obvious seasonal variation in precipitation.

Because of the difference between sea and land, the climate in Zhejiang displays distribution characteristics along longitudinal direction. It shows that, in winter, temperature is relatively low in the land area while high on the ocean. In contrast, in summer, the temperature increases progressively from ocean to land. Moreover, wind-force is relatively heavy year around. Gales blow more often and more powerfully in the littoral zone than inland. Fundamental wind pressure declines sharply from sea to land[7].

The climate also demonstrates distribution characteristics along latitudinal direction at the same time. Temperature is higher in the south than in the north. In 2004, the temperature was above 18 ℃ in most areas of the south, while below 18 ℃ in most areas of the north. Precipitation decreases from midwest and north areas to mideast and south areas. And evaporation does quite the reverse. The mean annual relative humidity is about 80% in the whole province, increasing from north to south, highest in July and lowest in January.

Then the factors are analyzed based on the natural conditions.

3.2.1 Environmental chloride content

In Zhejiang Province, the most outstanding environmental factor affecting the durability of concrete structures is erosion caused by chloride. Chloride is the most dangerous erosion medium that concrete structures might meet with during service life.

Chloride content accounts for more than 90% of the salt in sea[8]. So the higher salt degree is, the larger the chloride content in sea water is. The salt degree of the surface water usually changes from 18 to 20 kg/m^3. It is relatively lower in the paralic environment of Zhejiang because seven rivers discharge into the ocean. For example, the salt degree in Hangzhou Gulf is even lower than 10 kg/m^3 because Yangtze River and Qiantang River discharge into the gulf [9]. It is indicated that the salt degree of the surface water in paralic environment fluctuates with seasons alternating and areas changing. No matter whether in winter or summer, the salt degree increases progressively from north to south[7].

In the coastal environment, the chloride content in the atmosphere increases with that in the surface water of the adjacent sea increasing, the wind-speed increasing and the distance from the coast decreasing. Ref. [8] presented that the content of salt-fog in the air decreases exponentially with the distance from the coast increasing, which is close to the normal environment out of 3 000 m distance from the coast. Ref. [10] proposed the surface chloride concentration values under different environmental conditions. Ref. [11] carried on research on 1 158 bridge structures and concluded that the surface chloride concentration is related to the distance from the coast in the inshore atmospheric environment, see Fig. 1.

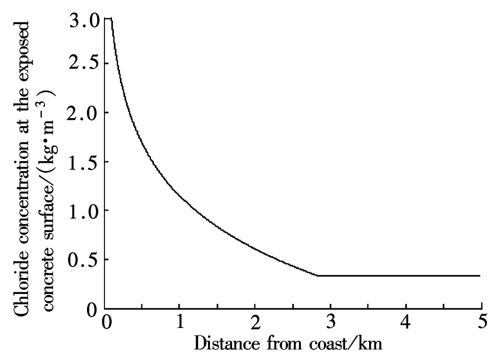

Fig. 1 Chloride concentration at the exposed concrete surface with the distance from the coast

From above it can be concluded that the chloride content in the air less than 100 m distance from the coast is close to that in ocean-atmosphere.

Serious durability degradations are found in some early inshore bridges due to sea sands cast in as fine aggregate, from which the chloride inside aggravates the durability degradation.

Without sea wind and sea water, concrete bridges built inland in Zhejiang also suffer from chloride erosion caused by acid rain. It is worth researching but needs collecting plenty of data and actual measurements. Further research work on this topic will be carried out.

3.2.2 Temperature

Temperature has a double influence on the durability of concrete: on the one hand, temperature rising accelerates the evaporation of the moisture, causes the superficial porosity to increase, thereby increasing the permeability of concrete; on the other hand, temperature rising promotes concrete hydration inside, consequently, increasing compactability and reducing permeability. It also accelerates the carbonization course of concrete and promotes corrosion of the reinforcing bar. High temperature increases the final value of chloride diffusion coefficient[12].

Meteorological material available show that the variance of mean monthly temperature is about 3 ℃ among all counties in Zhejiang Province. And mean annual temperature is even closer. Hence, neglect of such tiny variance would not influence the rationality of the durability zonation of Zhejiang Province.

3.2.3 Environmental relative humidity (RH)

RH is an important factor influencing structural durability, which is generally acknowledged and confirmed by a number of tests and experiments.

RH plays an important role in chloride erosion. The humidity of concrete is quite influential to chloride diffusion coefficient because the chloride ingress from surface to inside, which consists of absorption, diffusion and permeation, needs pore water as a carrier. And there is some relationship between the humidity of concrete and RH. Rehabcon provided data of moisture transport coefficients for OPC-concrete of conventional *w/c*-ratio, shown in Tab. 1[13]. These coefficients are fairly constant as long as RH is below 65%. But with RH increasing they grow rapidly when RH is around 90% and much more sharply when RH is above 90%. So the larger RH is, the faster chloride migrates and the faster the reinforcing bars are corroded.

Tab. 1 Moisture transport coefficients for OPC-concrete

RH/%	$\delta_c/(\mathrm{km}^2\cdot\mathrm{s}^{-1})$				
	$w/c=0.4$	$w/c=0.5$	$w/c=0.6$	$w/c=0.7$	$w/c=0.8$
33 to 65	0.13	0.14	0.15	0.18	0.18
70	0.19	0.20	0.19	0.19	0.30
80	0.28	0.33	0.38	0.40	0.37
84	0.35	0.45	0.64	0.58	0.48
86	0.39	0.59	0.83	0.77	0.60
88	0.46	0.82	1.18	0.99	0.76
90	0.53	1.02	1.74	1.44	1.34
92	0.57	1.48	2.6	2.3	2.4
94		2.2	4.3	3.4	6.8
95	0.70	2.8	5.4	4.4	12.7
96		4.3	7.8	6.4	19
97		9.0	11.7	10.0	28
98					53

RH plays a large role in concrete carbonization. Too high RH means that the concrete is under water all the time or humidity is close to saturation. CO_2 and O_2 can hardly diffuse within concrete, so carbonization proceeds slowly or not at all. Too low RH means that the concrete is dry, the carbonization can reach the surface of the reinforcing bar comparatively fast but the reinforcing bar can hardly be rusted at that moment. It is shown in tests that concrete carbonization grows fast when RH is 50% to 80%[3].

RH also plays a large role in corrosion of the reinforcing bar. When RH is lower than 50%, the reinforcing bar cannot be rusted because moisture cannot meet the needs of electric chemical reactions in the concrete. When RH grows above 80%, corrosion of the reinforcing bar develops fastest. And it declines with RH above 90% because oxygen is difficult to diffuse, although some testing results indicate that the declination is indistinctive[3].

Therefore, RH is a quite important environmental factor which affects various kinds of degradation.

3.2.4 CO_2 density

CO_2 density has an effect on carbonization of concrete that the higher the density is, the faster the carbonization proceeds[12].

CO_2 density in ocean-atmosphere is well known to be lower than that in crowded city and industrial area. But air is flowing and CO_2 density is changing all the time at one site. Consequently, CO_2 density is not put into consideration here.

3.2.5 Wind-pressure and wind-speed

Wind-pressure accelerates carbonization. It has been indicated that, under the action of strong wind, the carbonization depth on the windward and the leeward sides of concrete columns is 1.5 to 2 times that on the other sides[3]. Qu et al. proposed a theoretical model to describe wind-pressure accelerating carbonization by means of experimental research[14]. Wind-speed influences the chloride content in the coastal atmosphere. The stronger the wind-force from sea is, the more salt-fog is taken to the land. Storms could take much as 10 times salt-fog content as normal wind[8].

Zhejiang is a province with a long coastline, along which strong winds often blow between sea and land. In the investigation of the highway bridges built in Zhejiang[15], the appearance on the windward and the leeward sides of concrete shows much more serious durability degradation than on the other sides. Research on influence of strong wind is meaningful especially in windy regions.

In Zhejiang Province, strong wind occurs mainly in the littoral zone. Wind-force and wind-speed reduce rapidly from coast to inland. The distribution of the fundamental wind pressure displays the same trend. So the impact of wind on durability can be considered along with the coastal environment of the littoral zone.

From the analyses above, the environmental factors which determine durability zonation of Zhejiang Province are selected as follows:

a) Chloride content in the surface of sea water (salt degree);

b) Distance from the coast;

c) RH.

4 Durability Zonation Map of Zhejiang Province

The durability zonation map of Zhejiang Province for durability design of highway bridges is proposed as an example. The map is worked out according to the selected environmental factors. DZ takes advantage of the Administrative Map for practical convenience.

1) Zonation on latitude direction: According to the distance from the coast, Zhejiang is zoned into three parts: the paralic area and littoral zone with a distance from coast less than 100 m, the littoral zone, and the inland area.

2) Zonation on longitude direction: According to the distribution of the chloride content (salt degree) in the surface of sea water, precipitation and RH, Zhejiang is zoned into two parts: the south part and the north part.

Thus Zhejiang Province is zoned into six parts as shown in Fig. 2.

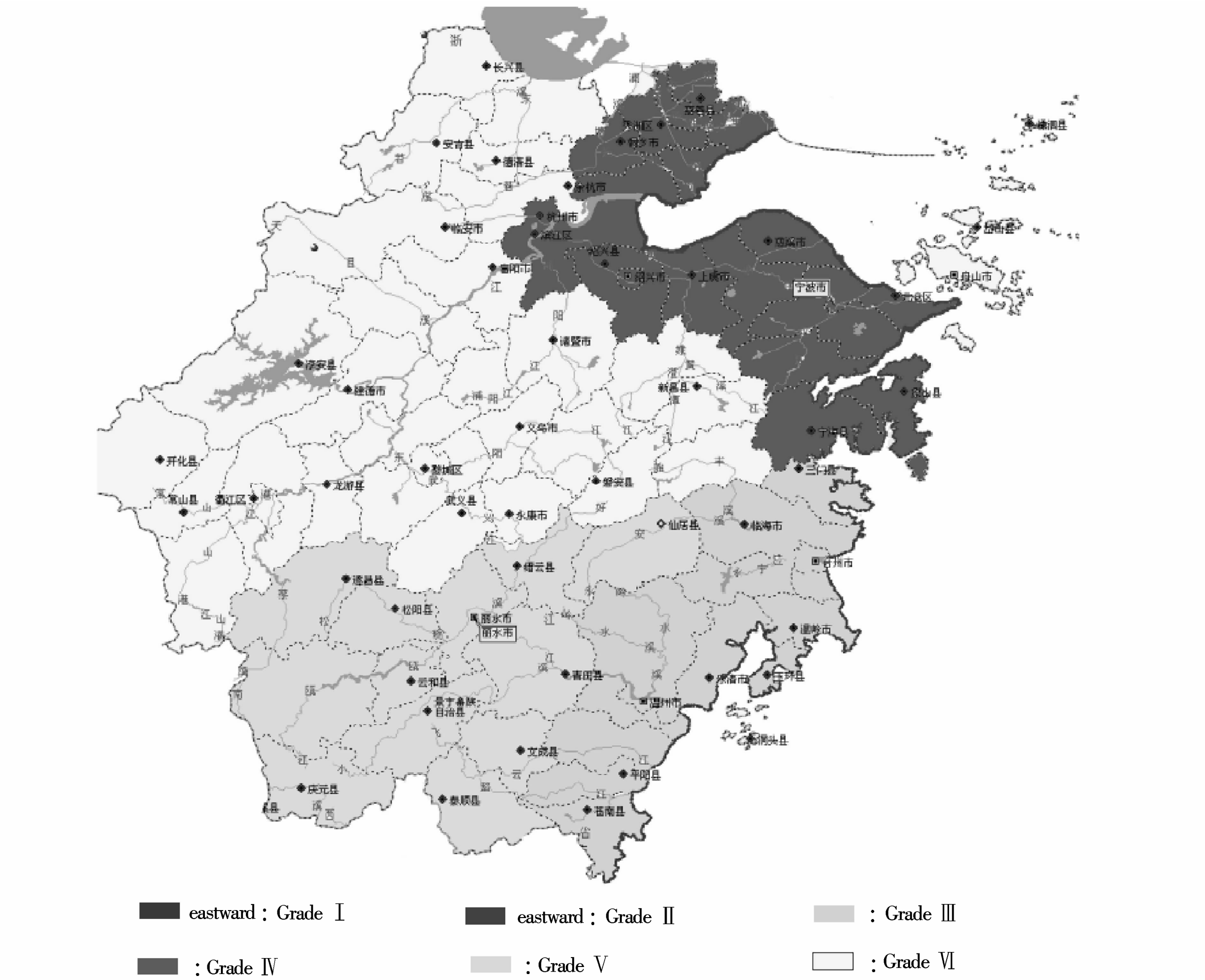

Fig. 2 Durability zonation map of Zhejiang Province

5 Guide Line on Concrete Structure Durability

According to the durability zonation map of Zhejiang Province, consulting the CEB/FIP guide[4] and *Guide to durability design and construction of concrete structures*[3], we confirm durability indices of the structure tentatively as follows: depth of concrete cover, concrete strength, *w/c* ratio, chloride diffusion coefficient and crack width.

Wetting-drying-alternation is the most dangerous working condition in atmospheric and coastal/oceanic environments. And durability usually degenerates most seriously in the members of bridge structures in water-splashing areas (water-lever-fluctuating areas). Therefore, different members with their respective positions and working conditions should be treated distinctively when the regulation of each durability index is made. And the grade of importance, structural type and function should also be taken into account.

The regulations are shown in Tabs. 2 to 5.

Tab. 2 Structure importance gradation

Grade of structure importance	Design service life as reference	Bridge and culvert structures
GSI-I	About 100 years	Super large bridge, important bridge
GSI-Ⅱ	About 50 years	Large bridge, moderate bridge, important small ridge
GSI-Ⅲ	About 30 years	Small bridge, culvert

Notes: ① Design service life should be confirmed according to owner' s demand, the values offered here are only for reference. ② The classification of bridge and culvert structures in the form refers to JTG D60—2004[16] form 1. 0. 11.

Tab. 3 Minimum depth of concrete cover mm

Environmental grade	Condition of member	Plane members (slab, wall, etc.)			Bar members (column, beam, etc.)		
		GSI-Ⅰ	GSI-Ⅱ	GSI-Ⅲ	GSI-Ⅰ	GSI-Ⅱ	GSI-Ⅲ
Ⅰ/Ⅱ	Water immersed zone	45	40	35	50	40	40
	Water splash zone	80/75	75/70	50	85/80	80/75	55
	Atmosphere zone	60/55	55/50	45	65/60	60/55	50
Ⅲ/Ⅳ	Water immersed zone	45	40	35	50	45	40
	Water splash zone	60/55	55/50	50	65/60	60/55	55
	Atmosphere zone	50/45	45/40	35	55/50	50/45	40
Ⅴ/Ⅵ	Water immersed zone	40	30	25	45	40	30
	Water splash zone	45/40	35/30	25	50/45	40/35	30
	Atmosphere zone	35/30	25/20	15	40/35	35/30	25

Notes: ①The strength grade and *w/c*-ratio of concrete should accord with the demands of Tab. 4. ② If the minimum cover depth in the form is less than the diameter of reinforcing bar, Cmin should be the same as the diameter of reinforcing bar. ③ If concrete is casted directly exposed to soil, the cover depth should not be less than 70 mm.

Tab. 4 Minimum concrete strength grade, maximum *w/c*-ratio and minimum amount of binding material kg/m^3

Environmental grade	Important grade		
	GSI-I	GSI-Ⅱ	GSI-Ⅲ
Ⅰ(Ⅱ)	C40, 0. 45, 320(300)	C35, 0. 50, 300(280)	C25, 0. 50, 300
Ⅲ(Ⅳ)	C45, 0. 36, 360(340)	C40, 0. 40, 340(320)	C40, 0. 40, 320
Ⅴ(Ⅵ)	C50, 0. 32, 380	C45, 0. 36, 360	C40, 0. 36, 360

Note: The data should accord with the demand of Tab. 3.

Tab. 5 Maximum crack width on exposed surface of concrete

Environmental grade	Condition of member	Reinforced concrete/mm	Prestressd concrete
Ⅰ, Ⅱ, Ⅲ, Ⅳ	Water immersed zone	0. 1	First class crack controlling
	Water splash zone		
	Atmosphere zone		
Ⅴ, Ⅵ	Water immersed zone	0. 3	Second class crack controlling
	Water splash zone	0. 2	
	Atmosphere zone	0. 3	

6 Conclusions

1) The theory of LCC is the foundation of DZS principles.

2) Determinant factors should be selected by the analyses of environmental conditions.

3) The whole range can be zoned into several parts according to selected factors, each part corresponding to proper environmental grade respectively.

4) With comprehensive consideration of members, working conditions and positions, each durability index can be stipulated corresponding to DZ, as well as structural importance, structural form and function.

DZ of Zhejiang Province needs to improve by further data collection and more analyses of environmental factors. Research work on quantificational durability design methods based on the theory of SLCC is ongoing.

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混凝土结构设计耐久性环境区划标准

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摘要:混凝土结构耐久性环境区划标准的目的就是为混凝土结构耐久性设计提供合理的设计参数. 混凝土结构耐久性环境区划标准在结构全寿命周期成本原理基础上考虑了环境对结构的影响,并将结构的重要性、结构形式和功能等多方面因素一并纳入考虑之中. 首先给出了混凝土结构设计耐久性环境区划标准的概念和建立该标准的 3 个基本原则,其次根据自然环境条件和结构重要性等确定了区划的主要影响因素,然后以浙江省公路桥梁结构耐久性环境区划图的编制为例说明了混凝土结构耐久性环境区划的可行性与实用性,最后根据区划图给出了耐久性区划标准的若干设计规定.

关键词:耐久性区划标准;混凝土结构设计;区划图;全寿命周期成本

中图分类号:TU37