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Environmental Factors Influencing the Durability of Concrete Structures in Maine Environments

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ABSTRACT

Concrete structures built in marine environment may suffer serious durability problems. Focusing on the reaction between concrete materials and environmental conditions on structural durability, the coefficients of environmental temperature and chloride content are established. Referring to only experimental data tested following the procedure similar to the regulations in NT Build 443 (Concrete, Hardened: Accelerated Chloride Penetration) of North Europe, the relationship between D_{28} and water/binder ratio, which are converted into equivalent values of a standard reference environmental condition at 20ºC and a concentration of 165 g ± 1 g NaCl per dm^3 solution, using the established formula of coefficients of environmental temperature and chloride content, is presented. The converted results of different environmental conditions at laboratory and natural environment have a good agreement with each other, which indicates that the coefficients of environmental temperature and chloride content are reasonably determined. The ratio of wetting time per-period defined as the time proportion of concrete in wet conditions to the whole time period can be used to describe the dry-wet conditions in concrete. Analysis on the in-situ detected results shows that the penetration of chloride, the accumulation of surface chloride concentration and the decay of chloride diffusion coefficient are all related to the ratio of wetting time per-period. Subsequently, the formula of apparent chloride diffusion coefficient is proposed with consideration of surrounding temperature, sodium chloride solution concentration, age factor and altitude.

Keywords: Concrete durability, Marine environment, temperature, chloride content, ratio of wetting time.

1.0 INTRODUCTION

Deterioration of RC structures due to physical and chemical attack in different environments is a major topic in civil engineering. Gradually rising cost causing by the durability problems, such as carbonation, chloride penetration, sulphate attack, freeze-thaw cycles, salt-freeze, alkali-aggregate reaction, saline-crystallization, chemical-corrosive, etc. is also a large burden for the budgets associated with the maintenance of RC structures (Jin and Zhao, 2002). It is clear that a proper durability design method for RC structures is of crucial importance for engineers in order to prevent RC structures from corrosion and to fulfill the functional requirements of structures.

Generally, the exposure environments are divided into several categories on the basis of the durability deterioration mechanisms, and the erosion degrees of the environmental conditions are classified qualitatively for each environmental category (Mohurd, 2008.). These qualitative and experience-based design methods lack quantitative indexes and evaluations. As a consequence, environmental action level chosen for a same target project may be different by different engineers even in a same real case, leading to a different durability design which may fail the structure. Thus, it is necessary to establish a quantitative-based durability design method as guidelines for concrete structures.

Regional differences, induced by marine dynamic factors, coastal topography, climate and rivers inpouring into the sea, etc., are shown in the tidal nature, duration, movement mode, current direction and velocity, distribution of tidal range, etc. In different marine environments, the environmental temperature, the relative humidity, the chloride ion concentration, and the ratio of wetting time per-period of concrete during the penetration of chloride ion into the concrete are different. With these differences, on-site data in one environment can't be used as a reference for the prediction and assessment of the durability of concrete structures in another environment. Also, because of the huge differences between field and laboratory environment, a number of laboratory test data is difficult to be applied directly to predict the durability of concrete.

With the discussions of the influence of environmental temperature, the relative humidity, the chloride ion concentration, and the ratio of wetting time per-period of concrete, the quantification of the environmental factors influencing the durability of concrete structures under marine environments is obtained. Obviously, the test data in one specific area can be used in other areas with different environmental characteristics under the condition of lacking tested data.

2.0 INFLUENCE OF ENVIRONMENTAL FACTORS ON D_a

The penetration of chloride ions into concrete is the combination of several transport mechanisms due to concentration gradient, capillary action, electrical field and wick action et.al (Jin and Zhao, 2002). Generally, diffusion due to a concentration gradient is considered to be the primary mechanism which is usually described by Fick's second law. A typical error function solution of Fick's second law (Crank, 1979) is commonly introduced to analyse the chloride profiles in order to obtain the surface chloride content and the diffusion coefficient, which are regarded as a constant with time and independent variables. Considering the differences between real conditions in engineering and theoretical hypothesis in the solution of Fick's second law for chloride ingress into concrete(Thomas and Bamforth,1999), neglecting the initial chloride content in concrete as it is usually very low, an expression used in this paper is defined as follow:

$$C(x,t) = C_{sn} \cdot \left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_a t}} \right) \right] \quad (1)$$

where $C(x, t)$ is the chloride content at the depth x from the concrete surface with exposure time t, C_{sn} is the nominal surface chloride content, D_a is the apparent diffusion coefficient, and erf is the error function.

In Eq.(1), D_a are obtained by performing a nonlinear regression of Eq.(1) according to experimental data, which are not the real values at the time t but the equivalent average values during the time interval of t. Consequently, the obtained D_a can be directly bring into the error function solution of Fick's second law Eq.(1) to calculate the chloride content at a certain depth x at the corresponding exposure time t to avoid complex calculations such as integral when considering the time dependent of diffusion coefficient.

2.1 Apparent diffusion coefficient D_a

D_a represents the equivalent mean value of the chloride diffusion coefficient during the time period from initial exposure to detection. It has been generally recognized that D_a is a time-dependent variable and decreases with time because of the development of cement hydration, the reduce of pore distribution, the swelling of cement paste, the pore blocking effect due to chloride ingress, and the reaction of hydration products with chloride ions. The relationship between D_a and exposure time can be described as (Mangat and Molloy,1994):

$$D_a = D_0 \cdot \left(\frac{t_0}{t} \right)^n \quad (2)$$

where D_a and D_0 are the corresponding apparent diffusion coefficients at exposure time t and t_0; n is the age exponent related to concrete mixes and environmental conditions. Regarding t_0 as a standard reference time, D_a can be obtained by Eq.3 when D_0 is known. In practice, the reference time t_0 is commonly regarded as 28 days or 1 year.

2.2 Influence of environmental factors on D_a

Focusing on the reaction between concrete materials and environmental conditions on structural durability, a lot of standardization studies on test methods for corroded concrete have been accomplished to establish the influence law and relation equations corresponding to different materials and environments. Based on the study results (Wang, 2010), the coefficients of environmental temperature k_T and chloride ion concentration k_{Cl} can be expressed as:

$$k_{\mathrm{Cl}} = 3.48 - 1.20 C_{\mathrm{Cl}}^{1/3} \quad (3)$$

$$k_{\mathrm{T}} = \exp(3593(\frac{1}{T_{\mathrm{ref}}} - \frac{1}{T})) \quad (4)$$

where C_{Cl} is the chloride ion concentration of environmental solution (wt.%); T is the environmental temperature (K).

2.3 Determination of D_0 at a reference time t_0

The reference apparent diffusion coefficient D_0 is generally determined through the analysis of original detection data or by experience. In this paper, the reference time t_0 is regarded as 28 days.

D_{28} was determined referring to only experimental data tested following the procedure similar to the regulations in NT Build 443 (Concrete, Hardened: Accelerated Chloride Penetration) of North Europe (Nordtest,1995). Published data on the relationship between apparent diffusion coefficient and water/cement ratio were collected for OPC based concrete. Fig.1. shows the relationship between D_{28} and water/binder ratio w/b, which are converted into equivalent values of a standard reference environmental condition at 20ºC and a concentration of 165 g ± 1 g NaCl per dm^3 solution, using Eq.(3) and Eq.(4). As comparison, a suggested relationship between the chloride migration coefficient $D_{RCM,28}$

and *w/b*, suggested by LIFECON (Lay *et al.*, 2003), is also presented in Fig. 1. It can be seen that the converted results of different environmental conditions at laboratory and natural environment have a good agreement with each other, which indicates that k_T and k_{Cl} are reasonably determined. The suggested relationship between $D_{RCM,28}$ and *w/b* in Life-365 (Bentz and Thomas, 2013) is basically larger than the other data sets and can be regarded as the conservative values. Also, a good correlation is shown between D_{28} and $D_{RCM,28}$, which indicates that the value of migration coefficient can be used as a substitute when the apparent coefficient is not available and the reference time t_0 is relatively short, e.g. 28d.

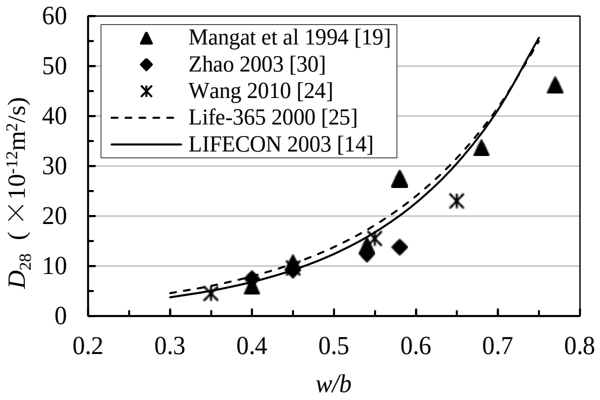

Fig. 1. Relationship between D_{28} and *w/b*

For security and conservative concerns, the suggested curve of D_{28} and *w/b* in Life-365(Bentz and Thomas, 2013) is introduced as:

$$D_{28} = 10^{(-12.06+2.4w/b)} \quad (5)$$

2.4 Age exponent *n*

Age exponent *n* is an empirical coefficient related to concrete mixes and environmental conditions. It is an important factor to the decay rate of concrete diffusion coefficient. Under the same environmental condition, the resistance of concrete to chloride ingression decrease largely with the decrease of *n*.

<u>Experimental work</u>

Feld detection was performed in Zhapu port of Jiaxing city, which is located in Zhejiang province, the eastern coast of China (Fig. 2.).

The region of Zhapu port belongs to a typical subtropical monsoon climate, with clear distinctions between the four seasons. The environmental characterisation comprises meteorological and hydrological characteristic data. The data were collected by headquarters of Hangzhou Bay Cross-

Fig.2. Region the experimental work took place

Table 1. Annual average value of environmental factors

factor	value	factor	value
Temperature / ºC	15.9	Relative humidity /%	82
Precipitation /mm	1250	Salinity /‰	10.79
pH	8.1	Mean tidal range /m	4.69
Wind speed / m·s^{-1}	3.2	Main wind directions	NW, SE

sea Bridge (Table 1.). The temperature shows large variation with a difference of 24.1 ºC between the average temperature of July and January. The relative humidity stays high, ranging from 79% to 85%. The wind direction is remarkably different in summer (SE) from that in winter (NW), and there are obvious seasonal variations in precipitation.

The experimental work of field detection consisted of two parts. The first one focused on studying the distribution of chloride penetration in concrete considering the spatial continuity in the vertical and the second concentrated on the probability characteristics and the variation of relevant parameters. For the first part, a concrete wall was chosen to detected with a 0.5m intervals in altitude from +1.30 m to +5.80 m , the Wusong Height Datum surface, respectively in Berth 1 of a second phase project (denoted as BN1-2). For the second part, specific points were detected and series of chloride profiles were obtained in different altitude for +2.3m, +5.25m (roughly located in splash or tidal zone divided by the Industry Standard of P. R. China. JTJ 275-2000(MOT, 2001)) from BN1-2. Concrete mix of 0.45 was used in the investigation.

Concrete power samples were extracted in situ from predetermined measuring points of each berth to obtain chloride profiles through drilling by percussion drill. The sampling depths were determined as follows: taken up to 70mm with intervals of 7mm. For each sample, the amount of the water-soluble chloride content was determined by RCT (Rapid Chloride Test) instrument in the laboratory following a procedure similar to that in ASTM C 1218 (Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration).

Results and discussions

After the field detection, chloride profiles were obtained and analysed. The chloride content profiles are shown in fig. 3. in which data of each profile are the corresponding mean values with same exposure time and altitude in each berth. Therefore, each profile in fig. 3. is the "mean curve" of 2~8 detection profiles. Number in the brackets of the legends in Figure 3 represents the exposure time (in month) till the detection.

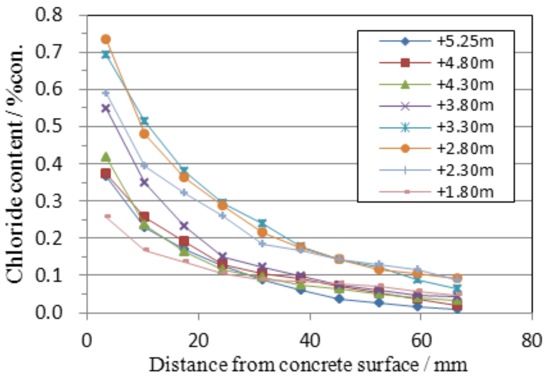

Fig. 3. Chloride profiles of concrete

A clear variation of chloride penetration into concrete over altitude is observed for measuring points. The surface chloride content of concrete and chloride content in the same depth from concrete surface increase with the altitude increasing and reach the maximum when the altitude is locate among +2.8m ~ +3.8m, and then decrease.

Based on the obtained chloride profiles and the related environmental conditions of BN1-2 (longest exposure duration, OPC-based concrete with water/binder ratio 0.45), age exponent n can be obtained by Eq.(2) with the achieved values of D_a (fitting a standard numerical solution of Fick's second Law) and D_0 (calculated by Eq.(3) ~ Eq.(5)).

Fig. 4a shows five curves to represent the relation between n and altitude h, in which each curve is the "average curve" of the corresponding detected data at the same detection conditions (altitude and exposure time). An increasing trend of n can be seen with the increase of altitude. By taking the value at +2.3m as reference (denoted as n_{ref}), Fig. 4b presents the relationship between n and the altitude h which is the mean value of the corresponding results in Fig.4a.. The following relationship can be found in Fig.4b:

$$n=n_{ref}\cdot k_{nh}=0.368\cdot e^{0.1h} \quad h>2.3\text{m} \quad (6)$$

where k_{nh} is the influence coefficient of altitude h to the age exponent n.

In Fig. 4a, it is can be seen that the values of n at +1.8m and +2.3m are similar except the curve at 197 month. Therefore, n decays with the decrease of h according to Eq.(6) until h reaches +2.3m, and then n is assumed to be a constant with the decrease of h.

Statistical analysis of n is done with data of the second part of the experimental work. n at different altitudes can all be considered to obey a log-normal distribution, with range of variation coefficient from 0.12 to 0.34. The statistical distribution of C_{sn} is thus defined as follows: Log-normal distribution, variation coefficient δ=0.30.

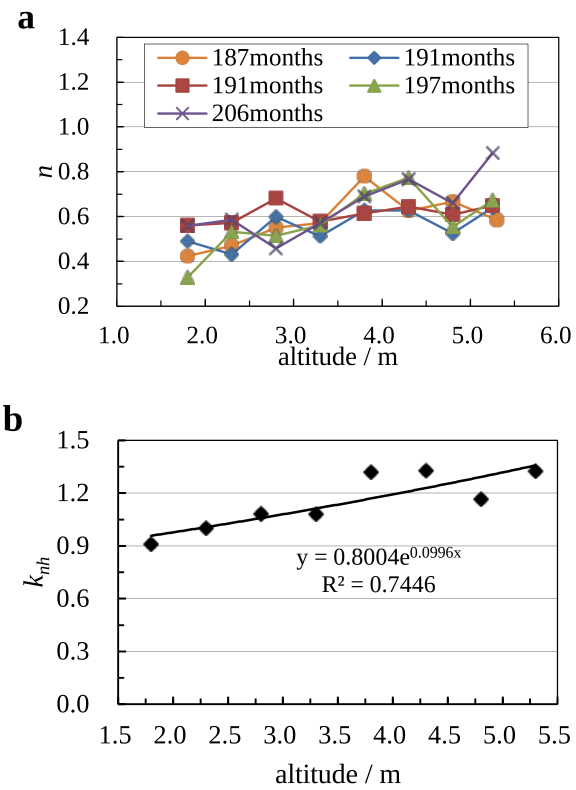

Fig. 4. Relationship between age exponent n and altitude h

Published data can be found on the relationships between n and water/binder ratio of concrete. The value of n is regarded as a constant in Duracrete (DuraCrete, 2000), Life-365 (Bentz and Thomas, 2013) and Bamforth (1999), but considered to increase with the increase of water/binder ratio by Jin (Jin, 2010) and Mangat et al (Mangat and Molloy,1994). Also, the value of n decreasing with the increase of water/binder ratio is reported in Wu and Cheng (2005). Therefore, there is no agreement on the relationship between n and concrete mixes.

3.0 ENVIRONMENT AND THE RATIO OF WETTING TIME PER-PERIOD

Regional differences, induced by marine dynamic factors, coastal topography, climate and rivers inpouring into the sea, etc., are shown in the tidal nature, duration, movement mode, current direction and velocity, distribution of tidal range, etc.

The distribution of chloride penetration into concrete along altitude is decided by the law of environmental factors changing along altitude. Thus, the distribution of chloride penetration into concrete changing with altitude is an intuitive surface phenomenon, which can only describe the environmental conditions in a specific sea area. Pore saturation inside concrete, evaporation rate of pore solution from surface and the dry-wet cycling regime are the three primary environmental factors influencing the durability of concrete structures in marine environments.

The ratio of wetting time per-period k_{JR} defined as the time proportion of concrete in wet conditions to the whole time period can be used to describe the dry-wet conditions in concrete. Analysis on the in-situ detected results shows that the penetration of chloride, the accumulation of surface chloride concentration and the decay of chloride diffusion coefficient are all related to the ratio of wetting time per-period (Yao, 2007). k_{JR} can not only represent the characteristics of the environments but also the changing law of concrete structural durability with the exposure environments.

Therefore, the ratio of wetting time per-period in concrete is the essence reflection of the environmental characteristics. It is a dominant environmental factor influencing the chloride penetration and determined as a common index to different coastal areas.

The calculation of k_{JR} at each altitude should refer to the tide level records within a relatively long period by statistical test. The detailed method can refer to the paper by Yao et al (Yao, 2007).

4.0 CONCLUSIONS

Concrete structures built in marine environment may suffer serious durability problems. The influence of environmental factors on the durability of concrete structures under marine environments, including environmental temperature, Relative humidity, chloride ion concentration content and the ratio of wetting time per-period of concrete, are discussed.

The coefficients of environmental temperature and chloride content are established. The relationship between D_{28} and water/binder ratio is presented. The ratio of wetting time per-period defined as the time proportion of concrete in wet conditions to the whole time period can be used to describe the dry-wet conditions in concrete.

Subsequently, the formula of apparent chloride diffusion coefficient is proposed with consideration of surrounding temperature, sodium chloride solution concentration, age factor and altitude.

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