- Technical Paper -

COMPREHENSIVE NUMERICAL SYSTEM FOR PREDICTING AIRBORNE CHLORIDE GENERATION AND ITS INGRESSION INTO CONCRETE UNDER ACTUAL ENVIRONMENTAL CONDITIONS

Rungrawee Wattanapornprom*1, Tetsuya Ishida*2

ABSTRACT

In marine environments, the deterioration of RC structures is caused by airborne chloride attacks. The structure used in coastal areas often requires repair due to the corrosion problem. Thus, this research aims to develop a comprehensive system that can predict chloride ingression into the concrete structures. The system can be used to determine the amount of airborne chloride generated by breaking waves, transported by wind flow, and ingression through the concrete surface at specified times and positions. The proposed framework is verified through onsite measurements to confirm its validity.

Keywords: Airborne chloride, generation, transportation, chloride penetration, washout

1. INTRODUCTION

Under airborne chloride environment, chloride concentration on the surface of concrete structure depends on the amount of airborne chloride supply, which varies due to wind direction, wind speed, wave height, obstacles, distance from the seashore, etc [1]. The concentration of airborne chloride at specific times and locations differs [2]. Moreover, when a structure is exposed to airborne chloride, chloride and water ingression do not occur uniformly on the concrete surface. Airborne chloride particles ingress into a concrete structure can be represented by the following processes: i) airborne chloride generation; ii) transportation; iii) surface adsorption; and iv) ingress through concrete surface [1]. Due to complex environmental conditions, existing models to predict chloride ingress into concrete for the direct exposure case, such as submerged condition or cyclic wetting and drying conditions, cannot be used to predict chloride penetration in case of airborne chloride attacks. Therefore, a particular model to predict chloride ingress into a concrete structure in airborne chloride environments is required. Moreover, in reality, the recorded of airborne chloride intensity data are limited. Although a numerical model to predict airborne chloride ingression is available, it may not be sufficient to evaluate the service life of the infrastructure. Thus, in such a case, it is also necessary to have a system, which can predict chloride ingression without recorded airborne chloride data.

Consequently, this research aims to develop a comprehensive system which can predict chloride ingression into concrete structures without past recorded of airborne chloride intensity. The comprehensive system can determine the amount of airborne chloride generated by breaking waves, transported by wind flow, and calculate its ingression into concrete. To determine the amount of airborne chloride ingression, calculations can be divided into two stages:

1) calculate the amount of chloride generation and transportation at a specified position;

2) calculate the water and chloride surface flux on the concrete surface and calculate the amount of chloride ingression inside cementitious material.

Each step can be conducted by using existing calculation models developed in past research. The relevant calculation models are shown in Fig. 1. If each calculation model is connected to each other, the system can determine the amount of the chloride ingression from the beginning of the generation processes. First, the amount of airborne chloride at a specified position can be calculated using the airborne chloride generation and transportation model [4]. After the airborne chloride amount is calculated, this data will be given as an input for the airborne chloride surface flux model [3]. By using this concept, it is possible to determine the amount of chloride ingression without recorded airborne chloride data. To complete the comprehensive system, each calculation model and the overall framework is verified through onsite measurements to confirm its validity.

2. AIRBORNE CHLORIDE GENERATION AND TRANSPORTATION MODEL

The modeling for airborne chloride generation and transportation was first developed by Kokubo and Okamura [4]. This model can be used to predict the amount of airborne chloride from generation and after transportation at each position. The model assumes that the wave breaking point is the initiation point of chloride production and airborne chloride is assume to distributes vertically along a vertical line passing through the initial point of the breaking wave.

*1 Researcher, Dept. of Civil Engineering, the University of Tokyo, Dr.E., JCI Member
*2 Professor, Dept. of Civil Engineering, the University of Tokyo, Dr.E., JCI Member

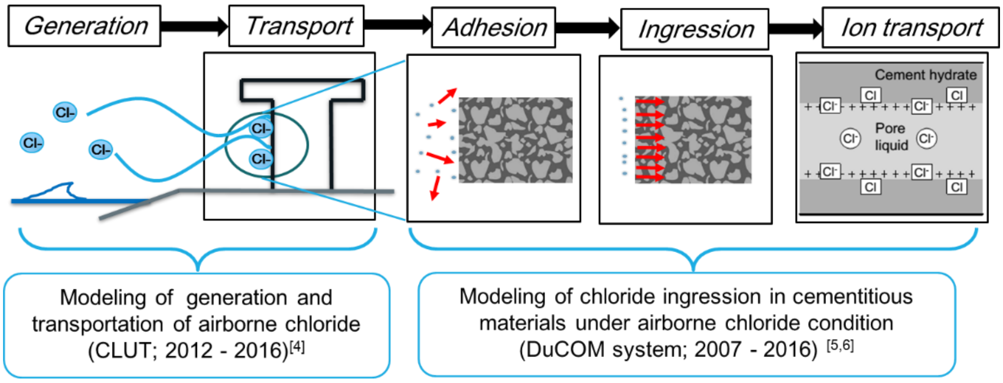

Fig. 1. Airborne chloride ingression process and relevant calculation models

From the observation results [5], wind velocity is not consistent and the wind velocity at the different heights is not identical. Thus in this verification, the authors have proposed a modified model, changing the wind velocity distribution in the vertical direction and the average size of airborne chloride. To verify the proposed model, onsite measurement data from previous observations were used. In the experiment, a dry gauze method with Japanese standard JIS Z 2382 was used. The dry gauze sample was attached on the surface of pier No. 2, Okawa Bridge in Niigata prefecture to capture airborne chloride. The distance from the bridge to the coastline was 150 m. For the calculation, wave height, tidal cycle, water depth, wind speed, wind direction, and rainfall intensity are necessary. Environmental data was taken from the previously recorded data from the following databases

- Wave height, tidal cycle and water depth are from the NowPhas Database at Sakata station;
- Wind speed and wind direction data received from AMEDAS Nezugaseki station.

The amount of airborne chloride at Okawa Bridge was calculated as shown in Fig. 2.

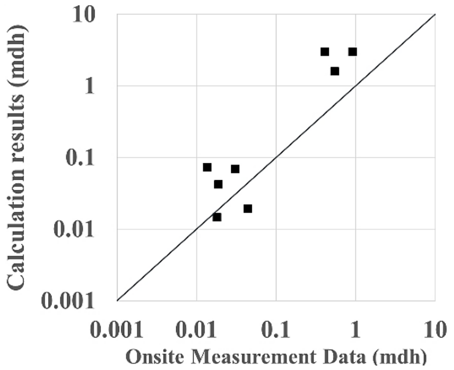

Fig. 2.Experiment and analysis results

3. MOISTURE AND CHLORIDE SURFACE FLUX CALCULATION UNDER AIRBORNE CHLORIDE ENVIRONMENTAL CONDITIONS.

In this paper, the Durability COncrete Model (DuCOM) is used in the analysis. DuCOM is a composite, multipurpose model that predicts the properties of concrete from the beginning of hydration. This computational system is capable of evaluating the early stage development of cementitious materials and the deterioration process of hydrated products under long-term environmental actions [6]. In this analysis system, mix proportions, environmental conditions, curing conditions, and other data are used as inputs for the calculation. DuCOM consists of several sub-models that work together and exchange data in real time. In this model, the development of micro-pore structures at early stages is obtained based on the computed degree of cement hydration. In moisture transport, both vapor and liquid phases of mass transport are considered. The moisture distribution and micro-pore structure information are inputs for the chloride transport model.

To simulate the mechanism of moisture and chloride penetration the concrete surface, wet and dry sections on the concrete surface have been assumed [3]. The proposed model in this study assumed that there is a thin layer on the concrete surface and the thickness of the layer is equal to 0.1 mm [7]. This thin layer represents the temporary storage for the water and chloride on the concrete surface.

After airborne chloride accumulated inside this layer, the water and chloride ion from airborne chloride particle start to penetrate through the concrete surface. The flux of water on concrete surface is calculated from the amount of water from airborne chloride particles.

The water flux from airborne chloride is represented by parameter Q_{air_water}, which is given as an input for the analysis. The volume of water that has penetrated into the concrete from the thin layer is Q_{in_water} (kg/m^2.s). The mechanism of the moisture and chloride behavior in the thin layer is shown in Fig.3.The amount of water on the concrete surface is represented by term S_{wet}, which is the ratio of the wet section in the thin layer.

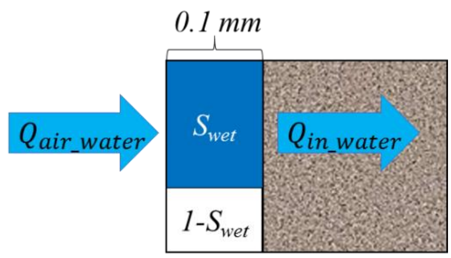

Fig. 3. Moisture transmission behavior in the thin layer.

In the calculation, the concentration of chloride in the water flux is 0.51 mol per liter, which is equal to the chloride concentration in sea water. The amount of chloride ions that have penetrated into the concrete is Q_{in_cl} (mol/m^2.s) as shown in Fig. 4.

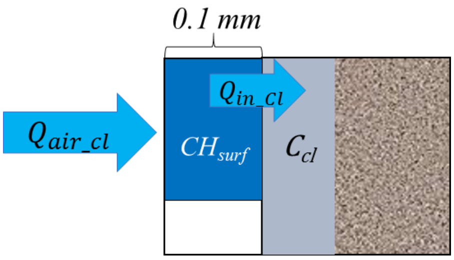

Fig. 4 Chloride ion penetration through the thin layer.

Parameter CH_{surf} in Fig.4 is the concentration of chloride on the concrete surface inside the thin water layer (mol/m^2).

3.1 Surface moisture penetration calculation

From Fig. 3, S_{wet}, is calculated by considering the mass balance equation between the flux of water attached on the concrete surface (Q_{air_water}) and water penetration into the concrete (Q_{in_water}). S_{wet} can be calculated as

$$\frac{S_{wet}}{dt} \times T \times \rho_w = Q_{air\_water} + Q_{in\_water} \,, \quad (1)$$

where T is the thickness of the thin layer, and ρ_w is the density of water (kg/m^3). Q_{in_water} is calculated based on the water penetration driven by the potential gradient between inside the concrete and the water on the concrete surface. Water penetration occurs only from the wet part of the thin layer. Since the relative humidity of the wet part can be considered to be the same as water = 1.0, the quantity of water that has penetrated, Q_{in_water}, can be expressed by

$$Q_{in\_water} = S_{wet} \times K_{water} \, (RH_{bound} - 1.0), \quad (2)$$

where K_{water} is the moisture transfer coefficient = 5.0 × 10^{-5} (kg / m^2.s), and RH_{bound} is the relative humidity inside the concrete surface, which is calculated in DuCOM system.

3.2 Airborne chloride penetration

The amount of chloride penetration from concrete surface is calculated by considering the chloride concentration on the concrete surface in the thin water layer. From Fig. 4, Q_{air_cl} (mol/m^2.s) is the airborne chloride flux on the concrete surface, Q_{in_cl} (mol/m^2.s) is the amount of chloride ions that have penetrated into the concrete structure, CH_{surf} (mol/m^2) is the concentration of chloride on the concrete surface inside the thin water layer, and C_{cl} is the chloride ion concentration inside the concrete surface (mol/l), respectively. In the computation, Q_{air_cl} can be calculated by considering the chloride concentration in the water flux on the concrete surface (Q_{air_water}), which can be calculated as

$$Q_{air\_cl} = \frac{Q_{air\_water} \times 0.51 \times 1000}{\rho_w} \,, \quad (3)$$

where Q_{air_water} (kg/m^2.s) is the flux of water containing airborne chloride particles attached on the concrete surface, which is given as an input of the analysis, 0.51 represents the concentration of chloride in the water particles (mol/l), and ρ_w is the density of water (kg/m^3).

In order to calculate the amount of chloride penetration into concrete, the diffusion and advection mechanisms are taken into consideration in the model. The model assumes that chloride penetration occurs only through the wet part in the thin layer. The total amount of chloride penetration can be considered as the sum of advection and diffusion of chloride into concrete. Q_{in_cl} can be expressed by

$$Q_{in\_cl} = Q_{adv} + Q_{diff} \,, \quad (4)$$

where Q_{adv} is chloride ion penetration by advection from the thin water layer into concrete (kg/m^2.s). Q_{adv} can be expressed by

$$\mathbf{Q_{adv}} = \frac{\mathbf{Q_{in\_water} \times CH_{surf} \times 1000}}{\boldsymbol{\rho_w}}, \quad (5)$$

Q_{diff} in equation (17) is the amount of chloride penetration through diffusion, which is caused by the potential gradient between the thin water layer and concrete surface (kg/m^2.s). Q_{diff} can be calculated as

$$\mathbf{Q_{diff} = S_{wet} \times K_{cl} \times (C_{Cl} - CH_{surf})}, \quad (6)$$

where K_{cl} is the chloride transmission coefficient = 1.0 × 10^{-3} (m/s). C_{Cl} is the concentration of chloride ions at the exposure surface (mol/l), which is calculated in the DuCOM computation model based on the amount of chloride penetration on the concrete surface. CH_{surf} can be determined by solving the mass conservation equation for the chloride ion content in the thin water layer, which can be formulated as

$$\mathbf{\frac{d(CH_{surf})}{dt} \times 1000 \times T \times S_{wet} = Q_{air\_cl} + Q_{in\_cl}}, \quad (7)$$

where S_{wet} is the value computed by Equation (1), and T is the thickness of the thin layer, which is equal to 0.1 mm. The value of CH_{surf} is limited to 5.4 mol/l, which is the concentration of saturated solution of sodium chloride.

3.3 Chloride reduction from washout effect

Chloride concentration on the concrete structure is influenced by the climate condition, location, rainfall and sunshine. Past research has been reported that rainfall particle can removed the chloride particle from the atmosphere. Water particles from rainfall can wash chloride out from the concrete surface.

However, from the past observation, when the specimen exposed to low intensity rainfall, some rainfall particles subjected on the concrete surface and absorb into the structure but no washout effect occurred. Thus, it is assumed that washout effect occurs only when the concrete subject to heavy rain.

To find the appropriate amount of rainfall for washout calculation, onsite measurement data [2] was used for the sensitivity analysis. The analysis was conducted by assuming that the washout effect will occur when the rainfall intensity is equal to 1, 3, and 5 mm/hr. The analysis results are shown as follows

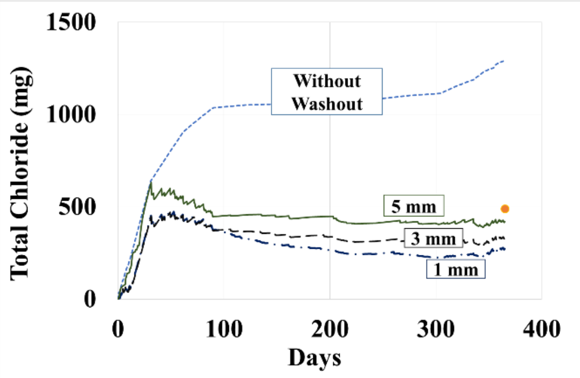

Fig. 5 Sensitivity analysis for determining the washout point.

The orange dot in the graph in Fig. 5 is the amount of the total chloride inside the specimen after exposure to airborne chloride conditions for 1 year. It can be inferred that when the rainfall intensity is equal to or exceeds 5.0 mm, the washout effect should be considered for the calculation.

To calculate the amount of chloride reduction from washout effect, the proposed model assume that CH_{surf} becomes zero when the washout effect occurs. At this stage, chloride ion inside concrete gradually diffuses from inside to outside, as shown in Fig. 6

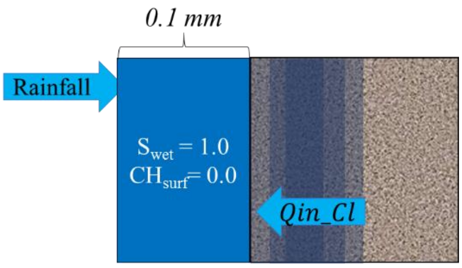

Fig. 6 Washout effect of rainfall on concrete surface.

Therefore, chloride ion penetration by advection will becomes zero and the amount of chloride reduction from diffusion effect can be calculated as

$$Q_{diff} = 1.0 \times K_{cl} \times (C_{Cl} - 0.0), \quad (8)$$

3.4 Verification of the proposed model

To verify the proposed, an experiment was conducted. The exposure experiment was started on October 10, 2014. The specimens were placed near the coastline to determine the amount of airborne chloride transportation and the amount of chloride ion ingress into mortar specimens. The exposure site was in Yamagata Prefecture, Japan. The exposure specimens were placed 150 m from the seashore. In the experiment, the tank sample was used to collect airborne chloride. The amount of airborne chloride was checked every month during the testing period.

Mortar test specimens with W/C 55% (size $10\times10\times10$ cm^3) were prepared. After curing under sealed condition for 7 and 91 days, each specimen was coated with epoxy around the specimen, except on the exposure surface, and carried to the exposure site. Each specimen was placed perpendicular to the ground, near by the airborne chloride capture equipment in the same direction. After exposure, the specimens were cut with 1 cm pitch and ground into powder for titration.

For the calculation, temperature, relative humidity, and precipitation data/hr were received from the AMEDAS database. The relative humidity data was from Sakata station. Temperature and precipitation data were from Nezugaseki station.

The total chloride distribution in the specimen was calculated with the proposed model. The results of the analysis and the experiment are shown in Fig. 7.

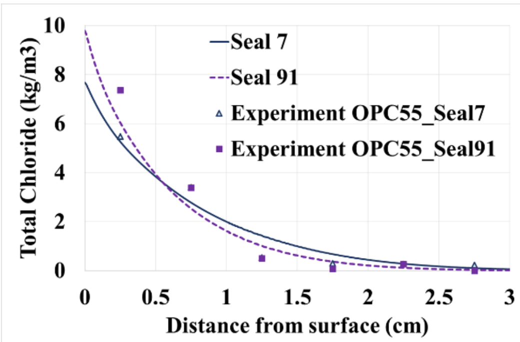

Fig.7 Chloride distribution from the experiment and calculation in the specimens.

The results show that the proposed model can simulate chloride penetration and the washout effect of specimens under actual environment conditions and with different mix designs. Furthermore, the analysis and testing results shows the clear difference between chloride penetration when the specimens are cured for different times.

4. VERIFICATION OF OVERALL FRAMEWORK TO CALCULATE CHLORIDE PENETRATION

In the previous section, the airborne chloride generation and transportation model and the airborne chloride ingression model have been verified. According to the verification results, when airborne chloride data is not available, the airborne chloride generation and transportation model can predict the amount of the airborne chloride. This data can then be used as an input for the surface flux model.

In this way, the total chloride inside the structure can be predicted. When recorded airborne chloride data are not available, the airborne chloride intensity can be calculated using wind speed, wind direction, rainfall intensity, breaking wave height, tidal cycle, and exposure conditions. The airborne chloride intensity, environmental data, and concrete mix proportions are given as an input into the DuCOM system to calculate chloride ingression.

To ensure the validity of the proposed system, chloride penetration data from the past research were used to verify the proposed framework

Yoshida S. et.al [8] observed chloride ingression under airborne chloride conditions at the Okawa Bridge. The Okawa Bridge is a pre-stressed I-Girder bridge located between Fuya and Nezugaseki train stations on the JR Uetsu Mainline in Niigata Prefecture. The length of the middle span is 19 m. The distance from the bridge to the coastline is ~150 m. Okawa Bridge was built in 1974. Due to corrosion problems on the bottom flange, bridge inspection was conducted in 1999. Around 29 cored concrete samples with a size of Ø5 cm x 6 cm were removed from I-Girder. The amount of chloride ingression was tested at every 2 cm pitch. For the verification, data from the core samples at the flange members in the girder of column No. 2 were used in the analysis. (Fig. 8).

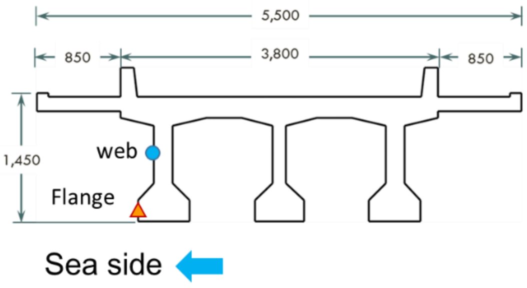

Fig 8 Position selected for verification.

4.1 Assumptions for the Calculation

For this calculation, the assumptions include:

1) when rainfall intensity is equal to 1 mm/hr, the rain blocks chloride particles and only water particles attach on the concrete surface;

2) the washout effect occurs when the rainfall intensity is equal to or higher than 5 mm/hr and only the flange position is subjected to rainfall;

3) as the mix proportion used in the construction does not appear in previous research, the mix design is that described in Table 1

Table 1 Assumed mix proportion for calculation.

W/C	Cement (kg)	Water (kg)	Sand (kg)	Gravel (kg)	% Air
0.45	400	180	780	980	2.3

4.2 Airborne Chloride Intensity Calculation

The calculation necessitates data for wave height, tidal cycle, water depth, wind speed, wind direction, and rainfall intensity. This data was taken from AMEDAS and NowPhas databases, as follows.

Table 2.The station for past data recorded

Data	Database	Station
Wind direction	AMEDAS	Sakata (1975–1976) Nezugaseki (1977–1999)
Wind speed (m/s)		Nezugaseki (1977–1999)
Precipitation (mm/hr)		Sakata (1975–1976) Nezugaseki (1977–1999)
Wave height (m)	NowPhas	Sakata (1975–1999)
Tidal cycle (s)		

The data were taken from the closest station to the Okawa Bridge. However, for wind speed and precipitation data in 1975 – 1976, the data from Nezugaseki station is not available. Thus, the data from Sakata station were taken instead. With this previously recorded data, the airborne chloride intensity was calculated as following

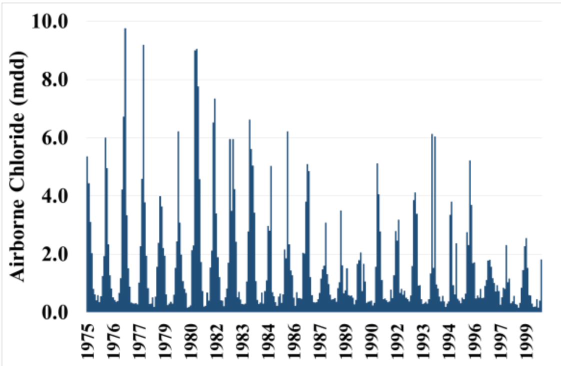

Fig. 9 Airborne chloride intensity from the calculation (1975 – 1999).

In the calculation, the amount of airborne chloride each year changed due to different wind directions, speed, and wave height.

The results show that the amount of airborne chloride during the exposure time was not constant. The amount of the airborne chloride changed due to environmental factors. Therefore, though previously recorded airborne chloride data is available, such records may not always be the most viable option for determining the chloride concentration of concrete structures.

4.3 Airborne Chloride ingression Calculation

The previous section, the amount of airborne chloride during 1975–1999 were calculated. These data are used as an input to calculate chloride ingression with the airborne chloride surface flux model.

To calculate chloride penetration, environmental data is needed. In this case, hourly temperature, relative humidity, and rainfall intensity data was received from the AMEDAS database, as shown in Table 3.

Table 3 The AMEDAS station for data.

Data	Station
Relative humidity (%)	Sakata (1975–1999)
Temperature (°C) and Precipitation (mm/hr)	Sakata (1975–1976) Nezugaseki (1977–1999)

The total chloride ingression according to the calculations is shown in Fig. 9. and Fig. 10.

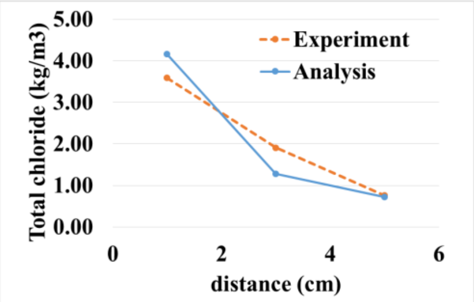

Fig. 9 Total chloride penetration at flange.

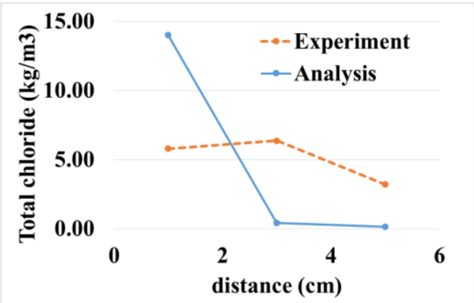

Fig. 10 Total chloride penetration at web.

The observations show the amount of chloride at the flange is lower than the amount at the web position. This may be because rainfall can attach to the flange surface and wash airborne chloride from the surface, reducing the total amount of chloride inside the material. The verification reveals that the proposed comprehensive system can calculate the total chloride at the flange position.

5. CONCLUSION

This study presents a comprehensive framework for calculating airborne chloride penetration. This framework can determine the amount of the airborne chloride generated by breaking waves, transported by wind flow, and its ingression in concrete. The proposed framework was verified with exposure tests under actual environmental conditions. From the verification results, the proposed comprehensive system can calculate the total chloride at a flange position. However, the analysis results at a web position did not match onsite measurement data. This may be due to limitations of the proposed system or the assumptions used in the model do not correspond to the actual exposure conditions. Thus, future modifications in the model should be considered.

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