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Comprehensive Numerical System for Predicting Airborne Chloride Generation and Its Ingress in Concrete under Actual Environmental Conditions

Rungrawee Wattanapornprom and Tetsuya Ishida

Abstract

The deterioration of concrete structures in airborne chloride environments is a common problem, as attested by the large number of concrete structures in coastal areas that are in need of repair due to corrosion of steel reinforcement. Thus, to prolong the service life of concrete infrastructure in marine environments, deterioration from airborne chloride should be carefully considered. However, the amount of airborne chloride is influenced by numerous factors including wind direction, wind speed, wave height, obstacles, and distance from the seashore, and the concentration of airborne chloride varies by time and location. Besides actual exposure conditions, chloride ingress depends also on the environmental condition. In order to design the concrete structures, one must consider the amount of airborne chloride, concrete qualities, and the environmental conditions. Consequently, this research aims to develop a comprehensive system that can predict chloride ingress in concrete structures by considering airborne chloride intensity at the specific locations and times, based on determination of the amount of airborne chloride generated by breaking waves and transported by wind flow. The proposed methodology can determine the chloride penetration into concrete structures in various marine environments. The numerical framework has been verified through on-site measurements to confirm its validity.

1. Introduction

Concrete structures near the coastline often suffer deterioration caused by airborne chloride. Chloride ion from airborne chloride accumulates on the surface of concrete structure, diffuses, and accelerates the corrosion of embedded steel bars. Thus, to prolong the service life of concrete structures in marine environments, the deterioration caused by airborne chloride should be carefully considered.

The main factor in the corrosion of a structure exposed to airborne chloride is the amount of chloride supplied from the surrounding environment. In recent standard specifications such as the Japan Society of Civil Engineers (JSCE) standard specifications (JSCE 2012), a simple method to consider environmental conditions in service is presented for the durability design of marine environment structures. In this scheme, the chloride concentration on the concrete surface \( C_o \) can be determined according to the distance of the target structure from the coastline. If the concrete structure is situated near the seashore, \( C_o \) will increase and a greater amount of chloride will be able to penetrate into the concrete structure. However, in the actual environmental conditions, \( C_o \) depends on the amount of airborne chloride, which varies depending on wind direction, wind speed, wave height, obstacles such as wave breakers and cliffs, distance from the seashore, and so on (Bongochgetsakul et al. 2011). Moreover, \( C_o \) is also affected by rainfall and melted snow as water can wash out chloride from the concrete surface (Yamashita et al. 2007; Wattanapornprom and Ishida 2017). Further, observational data from the Public Works Research Institute - PWRI (1993) show that the concentration of chloride on the concrete surface also depends on the concrete mix proportions. As a result, \( C_o \) of concrete differs according to the time, location and concrete qualities. Thus, the amount of chloride penetration cannot be determined satisfactorily based only on \( C_o \) from the distance of the target structure to the seashore.

To conduct the proper design, many researchers have carried out exposure tests to measure the amount of airborne chloride in different regions and environmental conditions. There are several methods to measure the amount of airborne chloride at a specified position. The dry gauze method standardized as JIS Z 2382 is one of the conventional methods to capture the amount of airborne chloride. However, this method is recommended to capture the airborne chloride only during a few hours. PWRI (1988) introduced the airborne chloride capture tank method which can capture the amount of airborne chloride in a longer period (more than one month). This method has been widely used in Japan (Nakamura et al. 2014). Meanwhile, in the other countries, some researchers alternately used the wet candle following ASTM G140 to check the airborne chloride amount (Meira et al. 2006; Hossain and Easa 2011). However, the capture tank and the wet candle require a large space in which to place the equipment. Thus, the equipment...
cannot attach on a precise position. Saeki et al. (2010) conducted the exposure test and introduced a thin mortar plate which is smaller than the capture tank equipment or wet candle. Consequently, it is easy to check the amount of airborne chloride at a specified position. Although there are several methods that can be used to capture the amount of airborne chloride, only few comparisons among the methods have been performed. Furthermore, measurement of the airborne chloride takes long time and need an equipment to collect the airborne chloride intensity, which leads to a high cost. Due to many difficulties, measuring the amount of airborne chloride at arbitrary times and locations is onerous and no much recorded airborne chloride intensity data is available. In addition, the amount of the airborne chloride during the test period can differ from actual exposure conditions during the service life of concrete structure.

Recently, a modeling of chloride ingress in concrete structure under airborne chloride environments has been developed (Wattanapornprom and Ishida 2017). This model can determine the amount of chloride penetration under actual environmental condition. However, it requires on-site measurement data with regard to airborne chloride. These constraints limit the applicability of the model. Therefore, the comprehensive system, which can predict the chloride penetration without measuring the actual airborne chloride amount, should be established.

The ingress of airborne chloride particles in a concrete structure can be represented by the following processes: i) airborne chloride generation, ii) transport, iii) surface adhesion, and iv) ingress through concrete surface (Bongochgetsakul et al. 2011) as shown in Fig. 1. In this paper, the authors propose a comprehensive system that integrates all these phenomena to predict chloride migration into concrete under various environmental conditions accurately. To determine the amount of airborne chloride ingress, calculations can be divided into two stages, as follows.

1) Calculation of the amount of chloride generation and transport at a specified location;
2) Calculation of the water and chloride surface flux on the concrete surface and calculation of the amount of chloride ingress inside the cementitious material.

Each step can be carried out by using the relevant models, as follows.

In the first step, the airborne chloride generation and transport model (Kokubo et al. 2009; Ishida et al. 2012) calculates the amount of airborne chloride at a specified location by using the existing environmental conditions in meteorological and wave information database, such as, wind speed, wind direction, rainfall, breaking wave height etc. (Fig. 1). In the second step, the airborne chloride ingress model developed by the authors (Wattanapornprom and Ishida 2017) calculates the amount of chloride penetration by considering the amount of advection and diffusion of airborne chloride on the concrete surface. The amount of chloride penetration into concrete depends on concrete mix proportions, curing conditions, relative humidity (RH), rainfall intensity, and various other factors (Wattanapornprom and Ishida 2017). Hence, the amount of airborne chloride from the first step and the environmental conditions and concrete mix proportions are used as an input for the

Fig. 1 Airborne chloride ingress process and relevant calculation models.
By connecting and coupling the models in the calculation, it is possible to predict the amount of chloride penetration through the existing meteorology data and ocean wave information without using the on-site measurement of airborne chloride data. Thereby, one can determine the proper design and service life prediction of the structure at the extensive location, time and quality of concrete in various marine environments. To reveal significant factors affecting airborne chloride intensity, on-site exposure tests were conducted by two different methods. Then, the experimental results were used to verify the airborne chloride generation and transport model. After the verification of the chloride generation and transport model, the proposed comprehensive system was verified with data from on-site measurements at a PC railway bridge as a demonstration of numerical simulation to verify the validity of the system.

2. Modeling of generation and transport of airborne chloride

The amount of airborne chloride differs by area. It has been reported that obstacles such as wave breakers and cliffs contribute to a higher amount of large-sized airborne chloride particles (Kokubo et al. 2009). Larger particles of airborne chloride tend to rapidly lose altitude under the force of gravity. However, smaller particles can be carried by the wind across long distances (Bongochgetsakul et al. 2011). Furthermore, the amount of airborne chloride at each location varies according to wind direction, wind speed, obstacles, and distance from the seashore (Bongochgetsakul et al. 2011; Kokubo et al. 2009). Faster wind speeds can carry more matter over longer distances and airborne chloride levels tend to be higher under higher wind conditions (Chen et al. 2013; Kokubo et al. 2009). Wind speed and wind direction change through the seasons, and thus the amount of airborne chloride varies depending on the season. The differences in airborne chloride intensity in each season are readily apparent in Fig. 2, which shows the exposure results obtained over a one-year period.

As previously mentioned, it is difficult to check the amount of airborne chloride at specific times and locations, and consequently, availability of recorded airborne chloride intensity data is limited. Thus, a reliable model that can predict airborne chloride intensity is needed. The modeling of airborne chloride generation and transport used in the proposed system was first developed by Kokubo and Okamura (2009) and Kokubo et al. (2009). This model can predict the amount of airborne chloride from generation and after transport at each location. The model assumes that the wave breaking point is the initiation point of airborne chloride production, and airborne chloride is assumed to distribute vertically along a vertical line passing through the initial point of the breaking wave. The total amount of airborne chloride (\( \theta_{\text{total}} \)) is assumed to be a function of the height of the breaking wave:

\[
\theta_{\text{total}} = \delta \cdot \theta_0 \cdot f(H_b) \cdot \frac{1}{T} ,
\]

where \( \theta_{\text{total}} \) is the total airborne chloride produced (particle number/m\(^3\)/s), \( \theta_0 \) is the referent number of the seawater aerosol produced, equal to \( 2.0 \times 10^4 \) particles/m\(^3\)/s, \( \delta \) is the coefficient of the place of airborne chloride production, \( T \) is the wave period (s), and \( f(H_b) \) is a function of the breaking wave height. In this case, \( f(H_b) = C \cdot H_b \), where \( C \) is a constant equal to 1.0.

The size of airborne chloride particles (d) produced at the same time is non-uniform. The size of airborne chloride particles at the initial point ranges from 10 \( \mu \)m to 5000 \( \mu \)m (Bongochgetsakul et al. 2011). The total number of airborne chloride particles of diameter \( d_i \) (particle number/m\(^3\)/s) can be calculated by integrating the density function in the range of \( \Delta d \):

\[
\theta_{d_i, \text{total}} = \theta_{\text{total}} \cdot \int_{d_i - \Delta d}^{d_i + \Delta d} \frac{1}{d_i} \exp\left(-\frac{1}{d_i} \cdot d\right) dd.
\]

It is assumed that the airborne chloride produced at the initial point is vertically distributed. The distribution function of airborne chloride is

\[
f(Z) = \frac{1}{Z_s} \exp\left(-\frac{Z}{Z_s}\right),
\]

where \( Z_s \) is the average height of the vertical distribution of airborne chloride (m), and \( Z \) is the height from the initial point (m). Regarding the vertical distribution of airborne chloride, it is assumed that higher wave height results in greater vertical distribution distance. \( Z_s \) can be expressed as a function of breaking wave height:

\[
Z_s = \varepsilon \cdot H,
\]

where \( \varepsilon \) is the coefficient for the vertical airborne chlo-

---

Fig. 2 Airborne chloride concentrations from October 1985 to November 1986 in Shinanogawa, Niigata Prefecture, Japan (Public Work Research Institute 1988).
ride distribution and $H$ is the wave height, which is equal to observed significant wave heights from the ocean wave database or the height of breaking waves for seashore conditions.

The amount of airborne chloride with diameter $d_i$ at height $Z_j$ can be found with:

$$
\Delta = \frac{\theta_{t_{a \rightarrow l}}}{\zeta} \int \exp \left( -\frac{1}{Z_j} \right) dz.
$$

In the model, it is assumed that airborne chloride transport is the process of moving the airborne chloride to a target point by the wind. Airborne chloride particles fall under the pull of gravity. The vertical distribution of airborne chloride particles in the wind is assumed to be constant during transport.

The total chloride at a specific location after the generation and transport of airborne chloride can be calculated as:

$$
\Delta = \frac{\theta_{t_{a \rightarrow l}}}{\zeta} \int \exp \left( -\frac{1}{Z_j} \right) dz.
$$

where $\theta_{t_{a \rightarrow l}}$ is the wave height, $d_i$ is the airborne chloride diameter (m), $\rho_p$ is the density of sea water (kg/m$^3$), $\rho_{air}$ is the density of air (kg/m$^3$), and $d_{ch}$ is the drag coefficient, calculated as:

$$
W_d = \frac{4gd_i}{3C_D \rho_{air}} \left( \rho_p - \rho_{air} \right) \frac{d_i^2}{\mu}.
$$

where $g$ is the acceleration of gravity (m/s$^2$), $d_i$ is the airborne chloride diameter (m), $\rho_p$ is the density of sea water (kg/m$^3$), $\rho_{air}$ is the density of air (kg/m$^3$), and $C_D$ is the drag coefficient, calculated as:

$$
C_D = \begin{cases} 
\frac{24}{Re} & \text{when } Re < 1 \\
0.55 + \frac{4.8 \sqrt{Re}}{Re} & \text{when } 1 < Re < 10^4
\end{cases}
$$

where $\mu$ is the dynamic viscosity of air (kg/m/s).

The coefficient and constants of the proposed model are given in Table 1.

From equation 6, the total number of airborne chloride particles with diameter $d_i$ at each location is calculated. The chloride ion intensity ($M_{cl_i} \cdot \text{kg/m}^3 \cdot \text{s}$) can be calculated from the total number of chloride particle as

$$
F_{d_{z_{i,j}}} = \frac{4}{3} \pi \left( \frac{d_i}{2} \right)^3 \cdot \rho_p \cdot \frac{Cl}{100} \cdot U.
$$

where $\rho_p$ is the density of sea water (kg/m$^3$), $U$ is the wind velocity (m/s), and $Cl$ is the concentration of chloride ions in sea water, equal to 1.9% by weight.

The total amount of chloride can then be determined through the summation of the total airborne chloride particles with diameter $d_i$, as shown in equation 11.

$$
F_{d_i} = \sum \theta_{d_{z_{i,j}}} \cdot \frac{4}{3} \pi \left( \frac{d_i}{2} \right)^3 \cdot \rho_p \cdot \frac{Cl}{100} \cdot U.
$$

However, the amount of chloride at each location is dependent on the wind direction. Equation 12 shows the amount of airborne chloride when the wind direction is normal to the concrete surface. When the wind deviates from this direction, the total chloride intensity can be calculated as

$$
F_{d_{z_{i,j}}} = \frac{4}{3} \pi \left( \frac{d_i}{2} \right)^3 \cdot \rho_p \cdot \frac{Cl}{100} \cdot U.
$$

where $\theta$ is the deviated wind direction from the normal surface.

To calculate the amount of airborne chloride, the exposure location and direction are important parameters to be considered. The north (N) direction is assigned as 0° and the angle increases clockwise, for example, east (E) is measured as 90°. The exposure direction is assigned as shown in Fig. 3.

In meteorological database, the wind direction is described as sixteen compass points (such as SSE, NNE.) as shown in Fig. 3. The different between each compass point is equal to 22.5 degree in true north-based azimuths unit. Since the airborne chloride cannot be captured on the concrete surface when the wind direction is in the perpendicular to the normal direction, the model assumes that the airborne chloride can attach to the concrete surface when the wind direction is ±67.5

| Table 1 Coefficients and constants for the proposed model. |
| --- | --- | --- |
| On shore | Beach | On open sea |
| $\delta$ | 1 | 10 |
| $\theta_0$ | $2 \times 10^4$ | |
| $d_i$ | 350 | 20 |
| $\epsilon$ | 8 |
| $d \geq d_i$ | 2.5 |
| $d < d_i$ | 40 |

where $\theta$ is the deviated wind direction from the normal surface.

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degree from the normal direction. An example is shown in Fig. 4. In this figure, the exposure direction is equal to 315°, therefore, airborne chloride particles can be captured when the wind direction is between 0–22.5° and 247.5–359°.

Past observation (Ishida et al. 2012; Wind Engineering Laboratory 1984) has shown that wind velocity at the same location but at different heights is not consistent. Higher up, wind speed tends to be higher. Thus, a power law is introduced to adjust the wind speed at the specified location. The wind velocity at the target location can be calculated as

\[ U = U_0 \left( \frac{z}{z_0} \right)^n, \]  

where \( U_0 \) is the wind speed from the meteorological database, \( z_0 \) is the reference height of the wind measurement position in the meteorological database, \( z \) is the chloride measurement position height, and \( n \) is the power law constant, equal to 7 when the exposure location is a near-seashore area and equal to 4 when the exposure location is in a residential area or far from the seashore (Kokubo 2009).

In the original model, average airborne chloride particle size was assumed to be constant depending on the exposure condition. However, from past observation (Ishida et al. 2012), the higher the breaking wave height, the larger the average particle size of the airborne chloride particles becomes. In addition, it has been reported that the water depth in the breaker zone (surf zone) near the coastline or in the shallow depth zone is around 5 m to 10 m (Reeve et al. 2004). According to wave physics, water depth limits wave height over a horizontal seabed (Byrne et al. 1986). The estimated maximum breaking wave height is around 55% of the water depth in shallow water areas where the seabed is almost horizontal, as is usually the case near the coastline (Byrne et al. 1986). Thus, in this paper, the maximum height of breaking waves at obstacles and at the seashore is assumed to be limited to 4 m, and the average airborne chloride particle size is suggested as follows.

Moreover, the amount of airborne chloride can be reduced by rainfall (Lewis et al. 2004). Thus, in the calculation, it is assumed that airborne chloride particles can be blocked by rainfall particles. When rainfall is higher than 1 mm/hr, airborne chloride particles are virtually absent (Kokubo et al. 2009), and no airborne chloride reaches the target location.

3. Airborne chloride intensity under actual environmental conditions

To identify the actual factors that affect airborne chloride intensity, experiments were conducted. As mentioned in the previous section, airborne chloride intensity varies according to many parameters, and the amount of airborne chloride can be different each year. For the durable design of reinforcing concrete structures in marine environments, airborne chloride intensity is one of the most important parameters. If the sampling process is conducted at a time when the amount of airborne chloride is low, suitable design cannot be achieved. Further, different values of airborne chloride may be obtained depending on the airborne chloride capture method that is used. Therefore, the objective of the experiments is to check for differences among the various capture methods and discrepancies in airborne chloride amount over long exposure periods. The experimental results are then used to check the validity of the proposed model.

3.1 Airborne chloride capture method

The exposure experiment started on October 10, 2014. In the experiment, a capture tank (Fig. 5) and mortar chip (Fig. 6) were used to collect airborne chloride particles. The capture tank method was developed by PWRI. Airborne chloride was deposited on a stainless-steel capture board connected by a plastic tube to a
plastic container. Airborne chloride on the capture board was washed off using pure water, which was collected in a plastic container. The size of the mortar chips used in this test was 40 × 40 mm² with a thickness of 5 mm. Mortar chip specimens were attached in different positions to check the airborne chloride intensity around the exposure area. The attachment positions of the mortar chips are shown in Fig. 7.

After the exposure, each mortar chip was ground into powder with a grinder. To find the amount of airborne chloride, the water inside the plastic container and the mortar powder were titrated by AgNO₃ to determine the airborne chloride amount. The chloride deposition amount was checked every 1 to 5 months during the testing period. The exposure dates and durations are listed in Table 3.

### 3.2 Exposure site and exposure condition

Figure 8 shows the exposure site location in Niigata Prefecture, Japan. The distance from the exposure to the coastline was 150 m. The average height of the mortar chips and the tank from the sea level is 4 m. The exposure condition was checked by on-site observation and with a bird’s-eye view. In front of the exposure position, the obstacles exist. The exposure condition around the testing location is shown in Fig. 9.

### 3.3 Experimental results

From the experiment, in the winter season (December to February), the amount of airborne chloride is relatively high compared with the summer season (May to August). Chloride intensity at the mortar chip in each position showed comparable results. Figure 10 shows the airborne chloride intensity of the variously placed mortar chips and Fig. 11 shows the airborne chloride intensity from each equipment.

---

**Table 3 Exposure dates and durations.**

| Exposure Date | Duration (days) |
|---------------|-----------------|
| Start | End |
| 10-10-2014 | 15-11-2014 | 36 |
| 15-11-2014 | 15-12-2014 | 30 |
| 15-12-2014 | 13-01-2015 | 29 |
| 13-01-2015 | 17-04-2015 | 94 |
| 17-04-2015 | 07-10-2015 | 173 |
| 07-10-2015 | 06-11-2015 | 30 |
| 06-11-2015 | 11-12-2015 | 35 |
| 11-12-2015 | 15-01-2016 | 35 |
| 15-01-2016 | 12-02-2016 | 28 |
| 12-02-2016 | 08-03-2016 | 25 |
| 08-03-2016 | 15-05-2016 | 68 |
| 15-05-2016 | 25-08-2016 | 102 |
| 25-08-2016 | 02-10-2016 | 38 |
| 02-10-2016 | 04-11-2016 | 33 |
| 04-11-2016 | 08-12-2016 | 34 |
| 08-12-2016 | 13-01-2016 | 36 |
| 13-01-2016 | 13-02-2016 | 31 |

---
From Fig. 10 and Fig. 11, the amount of airborne chloride during the period from October 2014 to January 2015 exceeded that of the same period in 2015. This is due to higher wind speeds and breaking wave heights in 2014. The wind speed and breaking wave height data are shown in Fig. 12. From the results, the amount of airborne chloride obtained from the tank clearly differed from the value from the mortar chips (Fig. 11). In the period from November 2014 to April 2015 and the period from January to February 2016, the amount of airborne chloride from the capture tank exceeded that from the mortar chips, but other than these periods, the amount of airborne chloride from the mortar chips tended to be higher than that from the capture tank. To discover the reason, additional mortar chips at positions 10 and 11 were attached to the tank to compare the amount of airborne chloride between the both methods. Figure 13 shows the values of chloride at mortar chip positions 10 and 11 compared to those of the capture tank. From the results, the amount of airborne chloride from the mortar chips at positions 10 and 11 was similar to that for the capture tank. The mortar chips at positions 1 to 9 on the stainless-steel shelf were attached on the column of the shelf, which has a slim shape and the wind can flow pass through the column. Meanwhile, since the capture tank is shaped like a wall, the wind cannot flow through the tank. Thus, there is a possibility that the differences are due to the variation of local wind speed at each position. Therefore, the additional investigation on local wind effect should be conducted in further study.
From the exposure experiment results, it can be inferred that the amount of airborne chloride obtained from the tank method and the mortar chip method can be similar when the equipment is installed at the same position. The amount of airborne chloride at different times differs depending on the environmental conditions, such as wind speed and breaking wave height. Thus, to check the airborne chloride intensity in a given location, the proper time, period and positioning of the equipment should be carefully considered and determined.

4. Verification of airborne chloride generation and transport model

To verify the airborne chloride generation and transport model, onsite measurement data from the experiment described in section 3 and data from previous research were used.

4.1 Verification of chloride distribution with mortar chip method

4.1.1 Exposure site and exposure condition

For the first verification, average airborne chloride intensity from the mortar chips at positions 1-9 in the previous section were used. The exposure condition considered in the analysis is the obstacle condition (Table 1 and 2). The exposure direction and obstacle location are shown in Fig. 14.

4.1.2 Environmental data

For the calculation, wave height, tidal cycle, water depth, wind speed, wind direction, and rainfall intensity are required. This environmental data was obtained from previously recorded data from the following databases:

1. Wave height, tidal cycle, and water depth data: The Nationwide Ocean Wave Information Network for Ports and Harbors (NowPhas) Database at Sakata station (NowPhas, 2014-2017) was used. In the calculation, the significant wave data were used. Although the wave height and the tidal cycle are recorded every 20 minutes in the database, one-hour averaged data was given to the numerical model.

2. Wind speed and wind direction data: Automated Meteorological Data Acquisition System (AMEDAS) of the Japan Meteorological Agency at Nezugasakei Station (Japan Meteorological Agency, 2014-2017) is used. The wind speed and the wind direction in the calculation per hour were given to the numerical model.

4.1.3 Experimental results and model verification

As previously mentioned, in the airborne chloride generation and transportation model, it is assumed that airborne chloride particles can be blocked by rainfall particles. When rainfall is higher than 1 mm/hr, airborne chloride particles are virtually absent (Kokubo et al. 2009), and no airborne chloride reaches the target location. In order to verify this assumption, the analysis was conducted with two different conditions; with rainfall effect and without rainfall effect. The results of the calculation are shown in Figs. 15 and 16.

From Fig. 15, when the rainfall effect is taken into account in the calculation, the amount of airborne chloride is reduced and the computed results become closer to the on-site measurement data. However, it should be
noted that this assumption is verified by the sensitivity analysis, therefore, the additional test to verify the assumption should be conducted.

By using the existing data from the meteorological database and wave information, the proposed model can be used to predict the amount of airborne chloride at specific locations when airborne chloride is captured by mortar chips. The experimental results showed that airborne chloride intensity in each season differs due to environmental conditions. Further, the proposed model can be used to estimate the amount of airborne chloride in different environmental conditions during the testing period (27 months).

4.2 Verification of total chloride penetration with tank capture method (PWRI; 1984 - 1987)
To confirm that the proposed model can be used in any type of climate and exposure conditions, additional analyses were conducted. The data for these analyses were obtained from experiments conducted by the PWRI between December 10, 1984 and December 9, 1987 in Japan to investigate the amount of airborne chloride and chloride penetration in various regions (Public Work Research Institute 1988). In this experiment, the tank capture method was used to collect airborne chloride. The amount of chloride was checked every month during the testing period.

4.2.1 Exposure site and exposure condition
Japan has a broad range of climates, from subarctic in the north to subtropical in the south. Therefore, recorded data from various exposure sites around Japan were selected. The exposure locations and conditions data come from a PWRI report (Public Work Research Institute 1988). The distance from the coastline, height, exposure condition, exposure direction, and duration are shown in Table 4.

| Position    | Distance (m) | Height (m) | Analysis conditions | Exposure direction | Duration (year) |
|-------------|--------------|------------|---------------------|--------------------|-----------------|
| Shinanokawa | 100          | 20.3       | Obstacle            | 337.5°             | 1               |
| Tsunouka    | 7000         | 15         | Seashore            | 275°               | 1               |
| Omori Bridge| 40*          | 9.0        | Obstacle            | 337.5°             | 1               |
| Sapporo Bridge| 9700        | 10         | Seashore            | 180°               | 1               |
| Orikasabashi| 400          | 3.0        | Seashore            | 90°                | 2               |
| Orikasa-Ohashi| 0           | 7.0        | Seashore            | 90°                | 3               |

* The distance of Omori bridge from the seashore is from data by Honma et al. (2005)

4.2.2 Environmental data
In this section, the rainfall effect is taken into account in the calculation. The environmental data was taken from the previously recorded data from the following databases as shown in Table 5. For the wave height, tidal cycle from NowPhas database, in 1984 – 1987 the data are recorded every two hours. Thus, in the calculation, it is assumed that the wave height and tidal cycle are the same in two hours. In addition, for rainfall, wind speed and wind direction the data are taken from AMEDAS database and the data in the calculation are the data per hour.

4.2.3 Experimental result and model verification
In the calculation, when the distance of the exposure position to the coastal line is larger than 1,000 m, it is assumed that the constant value n in equation (13) is equal to 4 (Wind Engineering Laboratory, 1984). The amount of airborne chloride at each exposure site as mentioned in Fig. 17 was calculated with the proposed model. The results are shown in Figs. 18 to 23.

From the verification results, the proposed model can approximately predict the amount of airborne chloride.
at specific locations when the airborne chloride is captured with the tank capture method. However, in some cases, the amount of airborne chloride from the calculation does not match the on-site measurement data. This may due to the restricted nature of the model, different wind speed at the exposure spot and the measuring station, or experiment error when the airborne chloride intensity is low.

5. Verification of overall framework to calculate chloride penetration

As mentioned, the chloride concentration on the concrete surface varies due to many factors and it is difficult to check the amount of airborne chloride at various times and locations. Consequently, it is necessary to develop a comprehensive system that can predict chloride generation, transport, and ingress under actual environmental conditions.

In section 4, the airborne chloride generation and transport model were verified. The verification results indicate that when recorded airborne chloride data are not available, airborne chloride intensity can be calculated using wind speed, wind direction, rainfall intensity, breaking wave height, tidal cycle, and exposure conditions. This data can then be used as input for the airborne chloride ingress model.

In this paper, for chloride ingress model, the Durability CONcrete Model (DuCOM) is used. 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 (Maekawa et al. 1999, 2008). In this analysis system, the 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 DuCOM, 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 ion transport model. From the previous research, each sub-model has been verified by the experiment under different conditions to validate the model (Maekawa et al. 1999, 2008; Ishida et al. 2007; Iqbal and Ishida 2009; Takahashi and Ishida 2016; Wattanapornprom and Ishida 2017). However, to predict the amount of airborne chloride penetration, the original DuCOM system cannot be used directly due to the different boundary conditions during airborne chloride exposure conditions.

When a structure is exposed to airborne chloride, only some parts of the structure are wet and other parts remain dry (Wattanapornprom and Ishida 2017). Thus, chloride and water ingress do not occur uniformly on
the concrete surface. Therefore, the boundary condition used in the calculation of chloride penetration under airborne chloride condition is different from that for concrete submerged in seawater. Furthermore, chloride concentration on the surface of the concrete structure is also influenced by rainfall (Yamashita et al. 2007). Thus, in order to obtain reliable results, these boundary conditions including the washout effect of chloride concentration on the concrete surface should be considered in the calculation.

As a result, the calculation of chloride and moisture flux on the concrete surface under airborne chloride exposure and rainfall exposure were introduced into the DuCOM system. The proposed model calculates the amount of chloride penetration by considering the amount of advection and diffusion of airborne chloride on the concrete surface. Previous research by the authors showed that when proper airborne chloride data and reliable environmental data are used, the proposed model can simulate airborne chloride penetration under actual environmental conditions. In addition, the proposed model can also calculate the amount of chloride penetration for different mix designs and different curing conditions (Wattanapornprom and Ishida 2017).

Thereby, by connecting the airborne chloride generation and transport model and the airborne chloride ingress model together, the total chloride penetration inside the structure can be predicted. The airborne chloride intensity, environmental data, and concrete mix proportions are used as input into the DuCOM system to calculate chloride ingress. The overall framework and information flow of the proposed system are shown in Fig. 23. To ensure the validity of the proposed system, chloride penetration data from on-site measurements was used for verification purposes.

5.1 Verification of Proposed Framework by the experiment
The exposure experiment was conducted at the same time as the experiment described in section 2. In the test, mortar test specimens measuring 10×10×10 cm³ were prepared as shown in Fig. 25. The objective of this exposure test was to determine the amount of airborne chloride ingress for specimens under different mix design conditions.

5.1.1 Specimen preparation
The specimens were water cured for 28 days, then coated with epoxy and carried to the exposure site. After exposure for 3 months (October 2014 to January 2015), the specimens were cut into 1-cm thick slices (Fig. 26) and ground into a powder for titration.

The mix design of the mortar used for the verification is given in Table 6.

| Mix   | W/B | Cement (kg) | Water (kg) | Sand (kg) | % Air |
|-------|-----|-------------|------------|-----------|-------|
| OPC55 | 55  | 691         | 380        | 1000      | 2     |

5.1.2 Environmental data for the analysis
For the analysis of chloride ingress in the mortar specimen, the environmental data described in Fig. 24 is needed. This time, the environmental data were collected from the nearest station in the existing database.

Fig. 25 Exposure specimen

Fig. 26 Titration sample preparation.
Temperature, RH and precipitation (mm/hr) were obtained from the AMEDAS database. The RH data was from Sakata station. The airborne chloride data came from the analysis results in section 4.1.

5.1.3 Experimental and analysis results

From the figure, the analysis was conducted with 2 conditions. Firstly, the analysis was conducted by using the amount of airborne chloride from on-site measurement data as described in section 3.3. Secondly, the airborne chloride amount is calculated from the airborne chloride generation and transportation model as shown in section 4.1.3. The analysis scheme is shown in Fig. 27. The experimental and analysis results are shown in Fig. 28.

Figure 28 (condition 1) shows that the airborne chloride ingress model can simulate chloride penetration under actual environmental conditions when the on-site measurement airborne chloride data is available. On the other hand, the amount of total chloride ingress yielded by the airborne chloride generation model (condition 2) slightly exceeded the experimental results. The reason is that the amount of airborne chloride from the model was higher than the actual amount of airborne chloride amount. From the results, it can be inferred that the comprehensive system is able to predict the amount of airborne chloride penetration with acceptable accuracy. This kind of analysis can be done by using only the meteorological and wave information data from the existing database (e.g. AMEDAS or NowPhas) to determine the chloride penetration depth. Thus, the on-site measurement is not necessary for predicting airborne chloride ingress into concrete.

5.2 Verification of Proposed Framework in a real structure

Additional verification by using the data from an actual RC structure was conducted. Yoshida S. et al. (1999) observed chloride ingress under airborne chloride conditions at the Okawa Bridge. The Okawa Bridge is a prestressed I-Girder bridge located between Fuya and Nezugaseki train stations on the JR Uetsu Main Line in Niigata Prefecture. The length of the middle span is 19 m. The distance from the bridge to the coastline is about
150 m. Okawa Bridge was built in 1974, and due to corrosion problems on the bottom flange, a bridge inspection was conducted in 1999. Around 29 cored concrete samples measuring Ø5 cm × 6 cm were removed from an I-Girder. The amount of chloride ingress was tested at 2 cm intervals.

For the verification, data from the core samples obtained from the flange and web members in the girder of column No. 2 were used in the analysis. Chloride ingress at the flange and web parts of the girder, which was directly exposed to the sea, was selected for the verification (Fig. 29).

5.2.1 Assumptions for the Calculation

The assumptions used for this calculation were as follows:
1) when rainfall intensity is equal to 1 mm/hr, the rain blocks chloride particles and only water particles reach the concrete surface (Wattanapornprom and Ishida 2017);
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) the amount of airborne chloride at the web and at the flange is identical;
4) as the mix proportions used in the construction is not known from previous research, the assumed mix design is that described in Table 7.

5.2.2 Exposure Site and Condition

The measurement position was at the Okawa Bridge in Niigata Prefecture, Japan. The distance from the bridge to the coastline is 150 m. The exposure site and condition are shown below.

The exposure condition was checked by on-site observation and from a bird’s-eye view (Fig. 31). Obstacles exist in front of the exposure site. The location of the obstacles is shown in Fig. 32.

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

Table 7 Assumed mix proportions for calculation.
The calculation necessitates data for wave height, tidal cycle, water depth, wind speed, wind direction, and rainfall intensity. This data was obtained from the AMEDAS and NowPhas databases, as shown in Table 8. Temperature, RH and precipitation data/hr were received from the AMEDAS database. The data were taken from the Nezugaseki station, which is the station closest to the Okawa Bridge. However, wind speed and precipitation data for 1975–1976 were not available from Nezugaseki station. Thus, the data from Sakata station was used instead. Using this historical data, the airborne chloride intensity was calculated as shown in Fig. 33.

The calculated amount of airborne chloride was different each year due to different wind directions, wind speeds, and wave heights. Figures 34 and 35 show the difference in airborne chloride intensity each year.

The results show that the amount of airborne chloride during the exposure period was far from constant. The amount of airborne chloride varied 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 on the surface of concrete structures.

Verification Results

The previous section described the calculation of the amount of airborne chloride during 1975–1999 with the airborne chloride generation and transport model. This data is used as an input to calculate chloride ingress 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 were obtained from the AMEDAS database, as shown in Table 9.

Total chloride ingress results obtained from the calculations are shown in Fig. 36 and Fig. 37.

| Table 8 Stations that recorded the data used for calculation. |
|---------------------------------------------------------------|
| Data | Database | Station |
| Wind direction | AMEDAS | Sakata (1975–1976) Nezugaseki (1977–1999) |
| Wind speed | Nezugaseki (1975–1999) |
| Precipitation | Sakata (1975–1976) Nezugaseki (1977–1999) |
| Wave height | NowPhas | Sakata (1975–1999) |
| Tidal cycle | |

| Table 9 AMEDAS data used for calculation. |
|-------------------------------------------|
| Data | Station |
| Relative humidity | Sakata (1975–1999) |
| Temperature | Sakata (1975–1976) Nezugaseki (1977–1999) |
| Precipitation | Sakata (1975–1976) Nezugaseki (1977–1999) |

Fig. 30 Position of Okawa Bridge Pier No. 2.

Fig. 31 Map of exposure position (from Google maps).

Fig. 32 Exposure condition near exposure site and location of obstacles (150 m from the seashore).
The observations show the amount of chloride to be lower at the flange than at the web. This may be because rainfall can reach the flange surface and wash airborne chloride from the surface, reducing the total amount of chloride inside the material.

The verification shows that the proposed comprehensive system was able to calculate total chloride at the flange position with fairly good accuracy. On the other hand, the analysis results show that the proposed framework cannot properly predict chloride ingress for concrete that remains dry, such as concrete under a roof slab covering. This may be due to limitations of the environmental and concrete mix design information, or to the use of incorrect assumptions in the proposed system.

6. Conclusion

This study presents a comprehensive framework for calculating airborne chloride penetration. The comprehensive framework consists of the airborne chloride generation and transport model and the airborne chloride ingress model. The airborne chloride generation and transport model has been improved and verified by on-site measurement data. By connecting two models together, the proposed framework can determine the amount of airborne chloride generated by breaking waves, transported by wind flow, and its ingress in concrete. The proposed framework was verified with exposure tests under actual environmental conditions. The verification results have shown that the proposed comprehensive system can calculate with fairly good accuracy the total chloride in a small size specimen as well as in real structures exposed to rain. This kind of analysis can be done by using only the meteorological and wave information data from the existing database (e.g. AMEDAS or NowPhas) to determine the chloride penetration depth. Thus, on-site measurement is not necessary for predicting airborne chloride ingress into concrete. However, the analysis results at the web position not exposed to rain did not match the on-site measure-
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