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Modeling of Chloride Penetration into Concrete under Airborne Chloride Environmental Conditions Combined with Washout Effects

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Abstract

In marine environments, deterioration of concrete infrastructures under airborne chloride attack is a common problem, which raises the need for a reliable prediction model of airborne chloride penetration into concrete structures to evaluate the service life of concrete structures. This study proposes a time-dependent computational model for predicting the amount of airborne chloride ingress into concrete under actual environmental conditions. The proposed model calculates the amount of chloride penetration by considering the amount of advection and diffusion of airborne chloride on the concrete surface. To compute the amount of airborne chloride penetration, the proportion of dry and wet sections on the concrete surface is assumed, and to ensure accurate prediction of chloride penetration into concrete structures under actual environment conditions, the washout effect of rainfall is taken into account in the calculation. The proposed model was verified through comparison of the experimental and on-site measurement results.

1. Introduction

In marine environments, the deterioration of reinforced concrete structures is caused by airborne chloride. Many infrastructures require repair or reconstruction due to the corrosion of reinforcing steel bars. Therefore, a reliable prediction model to calculate airborne chloride penetration into concrete structures is necessary to evaluate the service life of concrete structures.

Airborne chloride particle 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 (Bongochgetsakul et al. 2011) as shown in Fig. 1.

The amount of airborne chloride penetration depends on various factors, including the chloride concentration on the concrete surface, relative humidity, wind direction, and distance from the seashore (Bongochgetsakul et al. 2011). Additionally, under actual environmental conditions, the chloride concentration on the concrete surface can be affected by rainfall and melted snow. Water from rainfall or melted snow can wash out chloride from the concrete surface (Castro et al. 2001; Yamashita et al. 2007) and chloride inside the structure gradually diffuses out, which results in the reduction of the total amount of chloride in the concrete structure (Hong and Hooton 2000). This effect is called the washout effect. Its mechanism is shown in Fig. 2.

In this study, a time-dependent computational model that aims to predict the amount of chloride penetration into concrete both under control conditions and actual environmental conditions was developed. To enable valid prediction of chloride penetration into a concrete structure, both the phenomena related to chloride ion penetration in microstructures and the mechanism of chloride penetration under actual environmental conditions at macro-scale are taken into account in the calculation. The concrete mix design, curing method, amount of airborne chloride, temperature, relative humidity (RH) and precipitation data were collected and used as boundary conditions in a finite element analytical system.

In the system, modeling of airborne chloride is solved through combination with a cement hydration model, a micro-pore structure development model, and a moisture equilibrium and transport model, allowing the chloride migration process to be traced under arbitrary conditions in a unified way. The proposed framework is verified with both laboratory scale experiments and exposure tests under actual environment conditions.

2. DuCOM (Durability Concrete Model)

In this paper, the Durability CONcrete Model (DuCOM) is used in the analysis. DuCOM is a composite, multi-purpose 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, 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 com-
puted degree of cement hydration. In moisture transport, both vapor and liquid phases of mass transport are considered (Ishida et al. 2007). The moisture distribution and micro-pore structure information are inputs for the chloride transport model (Iqbal and Ishida 2009).

The boundary conditions for chloride penetration into concrete structures in the cases of sea water immersion and airborne chlorides differ. In the case of sea water immersion, the moisture flux and chloride concentration on the concrete surface are uniform. On the other hand, the concentration of chloride on concrete surface under airborne chloride condition is not constant. Under actual environmental conditions, the amount of airborne chloride at each position is changed due to wind direction, wind speed, obstacles, and distance from the seashore (Bongochgetsakul et al. 2011). Moreover, when the structure is exposed to airborne chloride, only some parts of the structure are wet and some parts remain dry. For this reason, 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 should be changed. In addition, chloride concentration on the concrete structure surface is also influenced by rainfall (Castro et al. 2001; Yamashita et al. 2007). Thus, in order to obtain the reliable results, the washout effect of chloride concentration on the concrete surface should be considered in the calculation.

To provide more reliable prediction, the calculation of chloride and moisture flux on the concrete surface under airborne chloride exposure and rainfall exposure conditions are introduced into the DuCOM system. Figure 3 shows the framework of the DuCOM system including the surface flux model for calculation of airborne chloride penetration. Onsite airborne chloride amount, temperature, relative humidity and precipitation data are needed as inputs for calculation.

3. Moisture and chloride surface flux calculation under airborne chloride environmental conditions

To simulate the mechanism of moisture and chloride penetration through the concrete surface, wet and dry sections on the concrete surface are assumed. The exposure direction of a structure in the calculation is assumed to be perpendicular to the horizontal plane. A previous study showed that water can be retained on the concrete surface and that the maximum thickness of the water layer is equal to 0.1 mm (Yasuda et al. 2013). Consequently, 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. This thin layer represents the temporary storage for the water and chloride on the concrete surface (Fig. 4).

After airborne chloride is accumulated inside this layer, the water and chloride ion from airborne chloride particles start to penetrate through the concrete surface. The flux of water on concrete surface is calculated from the amount of water existing in 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 mass of water that has penetrated into the concrete from the thin layer is $Q_{in\_water}$ (kg/m².s). The moisture and chloride flux through the thin layer is schematically shown in Fig. 5.

As shown in Fig. 5, the amount of water on the concrete surface is represented by the term $S_{wet}$, which is the ratio of the wet section in the thin layer. In the calculation, the concentration of chloride in the water flux is
set as 0.51 mol per liter, which is equal to the chloride concentration in sea water (3% by mass), and the amount of chloride ions that have penetrated into the concrete is $Q_{\text{in,cl}}$ (mol/m².s), as shown in Fig. 6.

Parameter $C_{\text{Cl}}$ in Fig. 6 is the concentration of chloride on the concrete surface inside the thin water layer (mol/m²).

### 3.1 Calculation of surface moisture penetration

Based on the concept shown in Fig. 5, $Q_{\text{air,water}}$ can be calculated from the measured amount of airborne chloride with the following equation:

$$Q_{\text{air,water}} = \frac{ABS \times \rho_w}{M_{\text{w}} \times 0.51 \times 1000},$$

where $\rho_w$ is the density of water (kg/m³), $M_{\text{w}}$ is the molecular mass of chloride, which is $35.45 \times 10^{-3}$ (kg/mol), and 0.51 is the concentration of chloride in the water particle (mol/l). ABS is the amount of airborne chloride (kg/m².s). The ratio of the wet part on the concrete sur-
face, $S_{\text{wet}}$, is calculated by considering the mass balance equation between the flux of water attached on the concrete surface ($Q_{\text{air\_water}}$) and water penetration into the concrete ($Q_{\text{in\_water}}$). $S_{\text{wet}}$ can be calculated as

$$S_{\text{wet}} = \frac{Q_{\text{air\_water}}}{\rho_{\text{w}}} + Q_{\text{in\_water}} \times t,$$

where $t$ is the thickness of the thin layer (assumed to be 0.1 mm), and $\rho_{\text{w}}$ is the density of water (kg/m$^3$). $Q_{\text{in\_water}}$ 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 1.0, the quantity of water that has penetrated, $Q_{\text{in\_water}}$, can be expressed by

$$Q_{\text{in\_water}} = S_{\text{wet}} \times K_{\text{water}} (\text{RH}_{\text{bound}} - 1.0),$$

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

### 3.2 Calculation of airborne chloride penetration

The amount of chloride penetration from the concrete surface is calculated by considering the chloride concentration in the temporary storage, i.e., in the thin water layer. From the concept in Fig. 6, $Q_{\text{air\_cl}}$ (mol/m$^2$.s) is the airborne chloride flux on the concrete surface, $Q_{\text{in\_cl}}$ (mol/m$^2$.s) is the amount of chloride ions that have penetrated into the concrete structure, $C_{\text{cl}}$ (mol/m$^3$) is the concentration of chloride on the concrete surface inside the thin water layer, and $C_{\text{cl}}$ is the chloride ion concentration of pore solution inside the concrete surface (mol/l), respectively. Since $Q_{\text{air\_cl}}$ corresponds to the chloride flux in the airborne chloride, it can be converted from $Q_{\text{air\_water}}$ as

$$Q_{\text{air\_cl}} = \frac{Q_{\text{air\_water}} \times 0.51 \times 1000}{\rho_{\text{w}}},$$

where $Q_{\text{air\_water}}$ (kg/m$^2$.s) is the flux of water containing airborne chloride particles attached to 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 $\rho_{\text{w}}$ is the density of water (kg/m$^3$).

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. $Q_{\text{in\_cl}}$ can be expressed by

$$Q_{\text{in\_cl}} = Q_{\text{adv}} + Q_{\text{diff}},$$

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

$$Q_{\text{adv}} = \frac{Q_{\text{in\_water}} \times C_{\text{cl}} \times 1000}{\rho_{\text{w}}}.$$

$Q_{\text{diff}}$ in Eq. (5) 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). $Q_{\text{diff}}$ can be calculated as

$$Q_{\text{diff}} = S_{\text{wet}} \times K_{\text{cl}} \times (C_{\text{cl}} - C_{\text{cl}}^\text{sat}),$$

where $K_{\text{cl}}$ is the chloride transmission coefficient at concrete surface = $1.0 \times 10^{-3}$ (m/s).

$C_{\text{cl}}$ can be determined by solving the mass conservation equation for the chloride ion content in the thin water layer, which can be formulated as

$$\frac{d(C_{\text{cl}})}{dt} \times 1000 \times t \times S_{\text{wet}} = Q_{\text{air\_cl}} + Q_{\text{in\_cl}},$$

where $S_{\text{wet}}$ is the value computed by Eq. (2), and $t$ is the thickness of the thin layer, which is equal to 0.1 mm. The value of $C_{\text{cl}}$ changes according to the given environmental condition: for example, in dry condition, $C_{\text{cl}}$ becomes higher due to moisture decrease in the thin layer. In such a case, the maximum concentration is set as 5.4 mol/l, which is the concentration of saturated solution of sodium chloride (Barrett 2003).

### 4. Moisture and chloride surface flux calculation under rainfall condition

#### 4.1 Calculation of surface moisture penetration under rainfall

The moisture penetration behavior under airborne chloride condition and rainfall condition differ. When the concrete structure is exposed to a humid environment, the moisture will gradually diffuse into pores driven by the gradient of vapor density. On the other hand, when the concrete surface is subjected to water, the concrete will absorb a large amount of water at the beginning due
to the capillary sorption mechanism. It is known from experiments and theory that the sorption flux is high at the beginning for a few hours and then declines sharply, depending on the porosity and connectivity of the porous network (Martys and Ferraris 1997).

Figure 7 shows the experiment and the analysis results from the previous research, when the specimens exposed to two different conditions (Iqbal and Ishida 2009). The experiment was conducted by using mortar specimen with W/C 0.35. After seal curing for 28 days, the specimens were exposed to 99.5% relative humidity environment and water submerged conditions for another 28 days. The weight of each specimen was checked regularly with an electronic scale. From the experiment, the results show that the moisture absorbed in water submerge conditions is higher as compared to the specimen exposed to relative humidity 99.5%.

In the DuCOM system, there are two options to define the boundary conditions in the analysis. For water submerge, positive pore pressure equal to the hydraulic head of water is applied to the exposed surface. For an unsaturated environment, the negative pore pressure computed with Kelvin’s equation is used (Iqbal and Ishida 2009). In a completely saturated condition, the calculation can be reproduced by applying hydraulic pressure at the surface node of the elements so that the sorption flux of liquid water can be simulated more realistically (Ishida et al. 2007; Iqbal and Ishida 2009) as shown in Fig. 7.

Under actual environmental conditions, the boundary condition when concrete exposed to airborne chloride and rainfall may differ. When concrete is exposed to airborne chloride condition, only small amount of water is supplied to the concrete structure. In this case, the boundary condition is closer to a humid environment. Besides, when the structure is subjected to rainfall and water from precipitation covers the concrete surface, the water from rainfall can be rapidly absorbed into concrete. This moisture penetration behavior would be similar to that of submerged condition. From this reason, the boundary condition in calculating the amount of water ingression into concrete under rainfall should be the same with water submerge case.

However, in reality, rainfall does not continue for a long time and rainfall intensity is not constant. Calculating moisture penetration under this condition with applied hydraulic pressure as described for the above treatment is difficult and time consuming. Thus, to calculate moisture penetration from rainfall, the magnified factor (MF) for moisture transfer is introduced in order to increase the water absorption capacity when the concrete surface is exposed to rainfall for a short time so that the sorption flux of liquid water can be simulated in a more realistic manner. The volume of water that penetrates into the concrete can be calculated as

\[
Q_{\text{in, water}} = S_{\text{wat}} \times MF \times K_{\text{water}} (RH_{\text{bound}} - 1.0),
\]

where \(K_{\text{water}}\) is the moisture transfer coefficient at concrete surface = \(5.0 \times 10^{-5}\) (kg / m·s), and \(RH_{\text{bound}}\) is the relative humidity inside the concrete surface.

The value of MF is assumed based on the sensitivity analysis. Figure 8 shows the results from sensitivity analysis using different values of MF. The results show that when a value of MF is set as 100.0, the amount of penetrated water (water gain) is close to applied hydraulic pressure conditions. Therefore, under heavy rainfall condition, MF = 100.0 is used to predict water ingestion.

4.2 Calculation of chloride reduction from washout effect

Chloride concentration on the concrete structure is influenced by the climate, location, rainfall and sunshine (Nuralinah and Shimomura 2012). Past research has reported that rainfall can remove chloride particles from the atmosphere (Lewis and Schwartz 2004). Besides, water particles from rainfall can wash out chloride from the concrete surface (Swatketitham 2004; Yamashita et al. 2007; EL-Desouky and Tsubaki 2012).

However, past observation has shown that when a specimen is exposed to low intensity rainfall (1-3 mm/hr), some rainfall particles land on the concrete...
surface and get absorbed into the structure but no washout effect occurs. Thus, it is assumed that the washout effect occurs only when the concrete is subjected to heavy rain (in this case, heavy rain is equal to 5.0 mm/hr). To calculate the amount of chloride reduction from the washout effect, the proposed model assumes that $C_{\text{Cl}}$ becomes zero when the washout effect occurs. At this stage, the chloride ion inside concrete gradually diffuses from inside to outside, as shown in Fig. 9.

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

$$Q_{\text{diff}} = 1.0 \times K_{\text{a}} \times (C_{\text{Cl}} - 0.0),$$  

(10)

5. Laboratory verification

To verify the proposed calculation system, a comprehensive experimental series was conducted under controlled conditions in the laboratory. Each experiment represents the phenomena that influence chloride penetration under airborne chloride condition.

5.1 Moisture penetration from airborne chloride particle

5.1.1 Experimental methodology

To simulate the airborne chloride condition, a wind tunnel was used (Nuralinah and Shimomura 2012). Inside the wind tunnel, a salt bath filled with NaCl solution of 3% concentration was installed. A bubble generator was placed in the salt bath to generate small salt particles, which were transported inside by the air flow generated by a propeller. The specimens were placed inside the wind tunnel to check water ingress. The overall layout of the wind tunnel used in the experiment is shown in Fig. 10.

5.1.2 Measurement of airborne chloride amount

As mentioned in the previous section, the proposed model in this study assumes that there is a thin layer that represents the temporary storage for the water and chloride on the concrete surface as shown in Figure 4. The flux of water on the concrete surface ($Q_{\text{air-water}}$) is calculated from the amount of water from airborne chloride particles by Eq. (1). Therefore, it is necessary to measure airborne chloride amount in the experiment and convert it to $Q_{\text{air-water}}$, which is given as an input for the analysis.

To find the amount of airborne chloride inside the wind tunnel chamber, the gauze and cotton specimens were placed inside the chamber. The specimen was prepared by using a cylinder plastic mold, size Ø 5 x 10 cm, filled with cotton and covered with gauze as shown in Fig. 11.

After 1 day of exposure, the gauze and cotton were removed and submerged in pure water to wash out the chloride from the gauze and cotton. Then, the amount of chloride in the water was determined by titration test.
5.1.3 Mortar specimen preparation
In this experiment, two mortar specimens consisting of Ø 5 x 10 cm cylinders with water-to-cement ratio (W/C) of 40% were prepared. After casting, the specimens were cured either under water or as sealed specimens for 30 days. After curing, each specimen was dried in an environmental control room (20°C, RH 60%) for 60 days. After drying, the exposure surface was grinded to a depth of 1-2 mm to control the quality and decrease the bleeding effect on the surface. Before exposure, each specimen was coated with epoxy except the exposure surface. During the test, the weight of each specimen was taken regularly by an electronic scale sensitive to three decimal places. A specimen is shown in Fig. 12.

5.1.4 Experimental results and model verification
In the proposed system, the environmental conditions, i.e. relative humidity (RH), temperature, and amount of airborne chloride are also taken into account in the calculation, as shown in Fig. 3. The values of \( S_{\text{wet}} \) and \( Q_{\text{in,water}} \) change if the environmental conditions change. Thus, the boundary conditions during the test are also an important parameter in the calculation. During the test, ambient temperature was 20°C. In the analysis, the relative humidity was assumed to be 90%. The experiment and analysis results for water ingress are shown in Figs. 13 and 14.

From the results in Figs. 13 and 14, with similar amounts of airborne chloride, the experimental and analysis results show the different amount of water ingress when the curing condition is changed. It can be concluded that the proposed concept can be used to calculate water ingress under controlled condition.

The analysis with the proposed model shows a good result for the seal curing case but a slight overestimation in the water curing case after the 10 days of exposure. The reason for the overestimation results could be from the inconsistence of the airborne chloride flux during the experiment. In the wind tunnel, wind speed at each position can be changed due to obstacles. Furthermore, if the level of the salt water is changed, the amount of airborne chloride at each position is also changed. Because of these factors, the amount of airborne chloride at each position inside the wind tunnel is not constant during the test.

5.2 Airborne chloride penetration experiment
5.2.1 Experimental methodology
In this experiment, the wind tunnel is also used to simulate the airborne chloride condition. In the experiment described in section 5.1, airborne chloride intensity was measured before the moisture penetration test, but due to the limitation of the equipment, the airborne chloride amounts at each position inside the wind tunnel are not constant. Thus, the modified airborne chloride measurement method was used in the experiment described in this section.

5.2.2 Specimen preparation
1) Mortar specimen
To determine the amount of chloride ingress, mortar specimens with W/C 55% were used. The specimens

![Fig. 11 Cotton and gauze specimen for measuring airborne chloride amount.](image)

![Fig. 12 Specimen for water ingress test.](image)

![Fig. 13 Experiment and analysis results for water ingress (water curing; chloride flux 1.01 mdh).](image)

![Fig. 14 Experiment and analysis results for water ingress (seal curing; chloride flux 1.19 mdh).](image)
were subjected to either underwater curing, sealed curing, or air curing for 30 days. After curing, each specimen was dried in an environmental control room (20°C, RH 60%) for 30 days before being exposed to airborne chloride. The mortar specimens used in the test are shown in Fig. 15.

2) Exposure specimen for finding airborne chloride flux
In order to make it possible to measure both the amount of airborne chloride and the amount of chloride penetration into the mortar specimen at the same time, a new type of exposure specimens was prepared. Each mortar specimen was coated with epoxy and placed in the middle of a Ø 10 × 20 cm plastic mold. In the outer area, gauze and cotton were placed to determine the amount of airborne chloride at each position. Between the mortar and cotton, super absorbent polymer (SAP) was placed to prevent the contamination of chloride droplets by the surface of the mortar specimen and the airborne chloride captured by cotton. The exposure specimens used in the experiment are shown in Figs. 16 and 17.

After 50 days, the amount of chloride in gauze and cotton was determined by the titration method to find the amount of airborne chloride at each position.

5.2.3 Specimen position
The exposure specimens were placed inside the chamber to find the amount of airborne chloride and chloride penetration. The exposure positions are shown in the following figure.

![Exposure positions in the experiment.](image-url)
5.2.4 Experimental results and model verification

From the experiment, the flux of airborne chloride inside the wind tunnel was found to be between 0.53 and 1.35 mdh (mg/dm²/hr) depending on the position. The amount of airborne chloride and relative humidity are shown in the following figure.

After 50 days of exposure, the amount of total chloride in each specimen was measured. The experimental and analytical results of chloride penetration are shown from Fig. 20 to Fig. 22. From the results, it has been confirmed that the proposed model can be used to calculate chloride penetration and water ingress under different amounts of airborne salt.

5.3 Washout effect experiment

5.3.1 Experimental methodology

For the verification of the proposed model under condition of washout by water, a washout experiment was conducted. In the experiment, W/C 40% and 55% mortar specimens, size Ø 5cm × 10cm, were prepared. After casting, the specimens were kept in an environmental control room (20°C, RH 60%) for 60 days to reduce the water content in the specimen and accelerate chloride adsorption. Before the washout experiment, the specimens were coated with epoxy materials and submerged in 3% salt water for 90 days.

After submerged to salt water, the specimens were placed on the slope and washed the surface by tap water. The water was flowing to keep the chloride concentration on the surface equal to zero during the testing period. From the past research, when the concrete surface is smooth and kept under wet condition, the amount of chloride reduction in the specimen are almost the same even though the specimen was washed under different exposure angle (EL-Desouky and Tsubaki 2012). In this test, the inclined plane 30 degrees from the horizontal was selected because the specimen can be placed stably. In addition, it is easier to control the direction of water compare with a steep slope.

Each specimen was washed with tap water for 6 and 60 days. The water used in the experiment was kept at 20°C. The water flow rate was equal to rainfall of 85 ml/min (5 mm/hr). The testing method is shown in Fig. 23.

5.3.2 Experimental result and model verification

After the specimens were submerged in the salt water or washed, powder samples were collected by using drilling machine 1-day after the exposure. The powder sample was titrated to find the amount of total chloride inside the specimen. The experimental and analytical results of chloride distribution are shown in Figs 24 and 25.

The results show that the chloride inside the specimen was reduced by the washout action and that the proposed model can be used to calculate the reduction of chloride penetration from the washout effect. However, in the
case of 60 days for W/C 0.55, prediction by the proposed model overestimates the amount of chloride washout at 0.75–1.5 cm. In the calculation, long exposure to water causes removal of the fixed chloride due to the chloride concentration gradient between the surface and interior of the specimen. This aspect remains for future study to enhance the accuracy and applicability of the model, although it has to be noted that there is no such long-term exposure to water (rain) in the actual weathering conditions, and the washout effect of short-term exposure to water plays a more important role in the calculation.

6. Field tests verification

The previous section verified the proposed model with experimental results. However, each experiment was tested under controlled conditions. To confirm that the proposed model can be used in actual situations, onsite measurement data from previous research is used for verification.

6.1 Model input

Past research has reported that rainfall particles can remove chloride particles from the atmosphere (Lewis and Schwartz 2004). Furthermore, past observations have shown that when specimens are exposed to low intensity rainfall (light rain), some rainfall particles contact the concrete surface and are absorbed into the concrete but the amount of water is not large enough to wash the concrete surface. In this case, no washout effect occurs. Thus, the assumptions for the analysis were assumed to simulate chloride ingress behavior in a more realistic manner. The assumptions can be divided into three parts as follows.

(1) Under airborne chloride condition (No rainfall, or when rainfall is less than 1 mm per hour)

In the case that the exposure surface of the structure is in the same direction with the capture equipment and they are close each other, it is assumed that airborne chloride intensity attached on specimen surface is the same as the amount of airborne chloride collected by the capture equipment.

When there is no rainfall or small enough rainfall (such as less than 1 mm per hour), only airborne chloride can attach on the concrete surface and chloride ion will gradually ingress into the concrete. $Q_{air\_water}$ can be calculated as

$$Q_{air\_water} = \frac{Q_{cap}\times\rho}{M_d\times0.51\times1000},$$

(11)
where \( Q_{\text{cop}} \) is the amount of airborne chloride from the airborne chloride capture equipment (kg/m\(^2\).s), \( M_c \) is the molecular weight of chloride, which is \(3.545 \times 10^{-3}\) (kg/mol), and 0.51 is the concentration of chloride in the water particle (mol/L).

(2) Under light rain (when rainfall is equal to or higher than 1 mm per hour)

In the calculation, it is assumed that airborne chloride particles can be blocked by rainfall particles (Lewis and Schwartz 2004). Therefore, in the calculation, it is assumed that when the rainfall amount is equal to or higher than 1 mm/hr, only pure water particles (chloride concentration equal to zero) can attach on the concrete surface. The amount of water is equal to the water amount from airborne chloride (from Eq. 11). In this step, the water transmission at the concrete surface is close to the humid environment. The washout effect will not occur but the chloride on the concrete surface is reduced due to the pure water particles attached on the concrete surface and the absence of chloride ion in the environment.

(3) Under heavy rain (when rainfall is equal to or higher than 5 mm per hour)

When a concrete structure is exposed to heavy rainfall and the amount of water is large enough to produce the washout effect, only pure water from the rainfall will attach on the concrete surface. At this stage, the chloride concentration on the concrete surface becomes zero. To find the appropriate amount of rainfall for washout calculation, testing data from the PWRI was used (Public Work Research Institute 1988) for the sensitivity analysis. The details of the experiment are discussed in section 6.2. The data from exposure site close to Shinanokawa River, Niigata prefecture was selected. The RH, temperature and rainfall intensity/hr were taken from the AMEDAS database at Niigata station. Moreover, it is assumed that when the temperature is lower than 3 °C, the precipitation in the AMEDAS database is snow (Meteorological Research Institute 1984). In the calculation, when there is snowfall, no washout effect occur and chloride ions can attach to the concrete surface. The sensitivity 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 sensitivity analysis results are shown in Fig. 26.

The orange dot in the graph in Fig. 26 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.

When a concrete structure is exposed to heavy rainfall (equal to or higher than 5 mm per hour), only the pure water from the rainfall will attach on the concrete surface. At this step, the chloride concentration on the concrete surface becomes 0. The value of \( Q_{\text{air_water}}\) (kg/m\(^2\).s) can be calculated by the following equation:

\[
Q_{\text{air_water}} = \frac{X \times 10^{-3} \times \rho_c}{60 \times 60},
\]

where \( X \) is the precipitation value (mm/hr).

To calculate the amount of moisture and chloride ingress under actual environmental conditions by the proposed model, first the wet section on the concrete surface (\(S_{\text{wet}}\)) is calculated (equation (2)). \(S_{\text{wet}}\) varies according to the concrete properties and environmental conditions. Then, if the specimen is exposed to airborne chloride (chloride amount in \(Q_{\text{air_water}}\) higher than 0), moisture penetration can be calculated by equation (3) and the chloride concentration on the concrete surface (\(C_{\text{cl}}\)) can be determined by equation (8). On the other hand, if the structure is exposed to heavy rainfall (higher than 5 mm/hr), the moisture penetration can be expressed by equation (9). The amount of chloride reduction from the washout effect can be determined by equation (10). The flow of the calculation of airborne chloride penetration into a concrete structure is shown in Fig. 27.

Using the above assumptions, verifications with on-site measurement data were conducted. Onsite measurement data were obtained from the various research papers. The verification was done by using the airborne chloride data from different collection methods, as detailed below.

6.2 Verification of total chloride penetration with tank collection method in Japan (PWRI; 1984 - 1987)

The first verification used data from experiments conducted by the Public Works Research Institute (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).

6.2.1 Airborne chloride capture method

A tank sample method was used to collect airborne chloride. This 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 the plastic container. After the test, the water inside the plastic container was titrated by AgNO₃ to determine the airborne chloride amount. The equipment used in the experiment is shown in Fig. 28.

6.2.2 Specimen preparation and exposure position
For the exposure test, a mortar with W/C 57.8% was used to make test specimens measuring 10×10×10 cm³. Each specimen was placed perpendicular to the ground, near by the airborne chloride capture equipment in the same direction. Figure 29 shows the exposure locations.
that were selected for model verification.

6.2.3 Environmental data
In the calculation, the air temperature, relative humidity and precipitation data received from Automated Meteorological Data Acquisition System (AMEDAS) of the Japan Meteorological Agency were used in the analysis. The data used in the analysis are the recoded data per hour. Each data was picked up from the nearest station from the exposure position. The station names are listed in Table 1, and an example of environmental data from AMEDAS is shown in Table 2.

6.2.4 Experimental results and model verification
The total chloride penetration into the mortar specimen was calculated by the proposed model. The results of the analysis and the experiment at each position are shown in Fig. 30 to Fig. 35.

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Table 1 Meteorological stations of AMEDAS for recorded data.

| Location       | Station Name | Location | Temperature (°C) | RH (%) | Precipitation (mm/hour) |
|----------------|--------------|----------|------------------|--------|-------------------------|
| Shinanokawa    | Niigata      | Niigata  | Niigata          |        |                         |
| Toumi Bridge   | Itoigawa     | Takada   | Itoigawa         |        |                         |
| Odawara        | Odawara      | Yokohama | Odawara          |        |                         |
| Omori Bridge   | Suttsu       | Suttsu   | Suttsu           |        |                         |
| Nagaegawa Bridge | Tottori   | Tottori  | Tottori          |        |                         |
| Henan Bridge   | Nago         | Nago     | Nago             |        |                         |

Table 2 Example of recorded meteorological data from AMEDAS (3 November 1987, 12:00 – 23:00 pm).

| Date, Time     | Station Name | Temperature (°C) | Precipitation (mm/hour) | RH (%) |
|----------------|--------------|------------------|-------------------------|--------|
| 03-11-87 12:00 | Niigata      | 18.0             | 9.5                     | 91     |
| 03-11-87 13:00 | Niigata      | 18.0             | 1.5                     | 91     |
| 03-11-87 14:00 | Niigata      | 18.0             | 0.0                     | 91     |
| 03-11-87 15:00 | Niigata      | 17.9             | 2.0                     | 88     |
| 03-11-87 16:00 | Niigata      | 17.9             | 0.5                     | 88     |
| 03-11-87 17:00 | Niigata      | 17.9             | 0.5                     | 88     |
| 03-11-87 18:00 | Niigata      | 16.9             | 1.5                     | 87     |
| 03-11-87 19:00 | Niigata      | 16.9             | 0.5                     | 87     |
| 03-11-87 20:00 | Niigata      | 16.9             | 0.0                     | 87     |
| 03-11-87 21:00 | Niigata      | 16.1             | 0.5                     | 84     |
| 03-11-87 22:00 | Niigata      | 16.1             | 0.5                     | 84     |
| 03-11-87 23:00 | Niigata      | 16.1             | 0.0                     | 84     |
The results from Fig. 30 to Fig. 35 show that the proposed model can simulate chloride penetration and the washout effect in mortar specimens under actual environment conditions. Furthermore, the proposed model shows a clear difference between chloride penetration under washout condition and without washout condition in the calculation. However, the results from the exposure test show that in some cases the analysis produces an underestimated or overestimated value compared with the experimental results. One of the reasons may be that the received methodological data is not the methodological data at the testing position.

As an example, Figure 36 shows the physical distance between the AMEDAS environmental data station and the test location in Okinawa Prefecture.

Another reason may also be that the assumptions used in the proposed model do not correspond to the actual exposure conditions. However, from this experiment, it should be noted that there is only one result at each exposure position. Therefore, due to the limitation of data, the additional verification is necessary for the future study.

6.3 Verification of chloride distribution with the tank collection method

This exposure experiment was started on October 10, 2014. The specimens were placed near the coastline to determine the amount of airborne chloride ingress for specimens under different curing conditions.

6.3.1 Airborne chloride capture method

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 (3 months).

6.3.2 Specimen preparation and exposure position

Mortar test specimens (size 10×10×10 cm³) were prepared. After curing under sealed condition for 7 and 91 days, each specimen was coated with epoxy and carried to the exposure site. After 3 months exposure, the specimens were cut with 1 cm pitch and ground into powder for titration. The mix proportions are given in Table 3.

The exposure site was in Niigata Prefecture, Japan. The exposure specimens were placed 150 m from the seashore (Fig. 37).

6.3.3 Environmental data

Temperature, relative humidity, and precipitation data per hour were received from the AMEDAS database. The relative humidity data was from Sakata station.
Temperature and precipitation data were from Nezugaseki station.

6.3.4 Experimental results and verification
The total chloride distribution in the specimen was calculated with the proposed model. To verify the effect of the rainfall and washout mechanism from the rainfall, the analysis was conducted. Figure 38 shows the analysis results when the concrete is exposed to the rainfall and without rainfall. It is assumed that the washout effect occurs when rainfall intensity is equal to or higher than 5 mm/hr. From the analysis, when the specimen exposed to the rainfall and the washout effect occur, the chloride on the surface reduce significantly. The depth of the chloride penetration is deeper than the case without rainfall.

Table 3 Mix proportions for exposure test.

| Mix   | W/C | Cement (kg) | Fly Ash (kg) | Water (kg) | Sand (kg) | % Air |
|-------|-----|-------------|--------------|------------|-----------|-------|
| OPC55 | 55  | 691         | 0            | 380        | 1000      | 2     |
| FA55  | 55  | 575         | 101          | 372        | 1000      | 2     |

The verifications for the different curing method and mix proportions were conducted by using the same assumptions. The results of the analysis and the experiment are shown in Fig. 39 and Fig. 40.

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.

6.4 Verification of total chloride penetration with wet candle method (Meira et al. 2007)
The objective of this exposure test is to determine the amount of chloride ingress in concrete in João Pessoa, Brazil.

6.4.1 Airborne chloride capture method
Airborne chloride in this study was measured with deposition on a wet candle device according to specifications established in the ASTM standard G140. These devices were placed at a height of 1.5 m from the

Fig. 37 Testing location in Niigata Prefecture, Japan (from Google Maps).

Fig. 38 Chloride distribution in the specimen with and without rainfall.

Fig. 39. Chloride distribution FA55 comparison between 7 days and 91 days curing.

Fig. 40. Chloride distribution OPC55 comparison between 7 days and 91 days curing.
ground. The chloride deposition on the equipment was collected every month for the testing period.

6.4.2 Specimen preparation and exposure position
Prismatic concrete columns of $15 \times 15 \times 140$ cm were cast using Brazilian cement CPIIF (filler-modified Portland). The mix design is presented in Table 4.

After exposure, core samples were taken from the column. Then, the amount of chloride inside the specimen was determined. The exposure site is shown in Fig. 41.

6.4.3 Environmental data
Climate data was collected from a Brazilian Government weather station located in the region where the research took place (Meira et al. 2007). However, for the model, the environmental data was taken from the reference paper (Meira et al. 2006).

6.4.4 Experimental results and verification
Total chloride penetration into the specimen was calculated with the proposed model. The results of the analysis and the experiment are shown in Figs. 42 and 43.

The analysis results match the experimental results. The proposed model can simulate chloride penetration when the airborne chloride is captured with the wet candle method. However, data for the verification is still limited. Moreover, the available environmental data is not precise. Therefore, further data is necessary to verify the wet candle method.

7. Conclusion
This study investigates phenomena that strongly affect the transport of chloride ion concrete materials under actual environmental conditions. A comprehensive analytical framework is proposed. An airborne chloride experiment, washout experiment and on-site measurement test were used to verify the proposed model. The results from the conducted experiments show that the proposed simulation model, where a proportion of dry and wet sections in a thin layer on the concrete surface is assumed, may be used to predict the level of moisture and airborne chloride penetration.

The verification results also show that when the specimen and capture equipment are exposed to airborne chloride in the same direction and reliable environmental data is used, the proposed model can simulate airborne chloride penetration under actual environmental condition. However, in some cases, the analysis results do not agree with the actual measurement data. Moreover, it should be noted that in some verifications there is only one result at each exposure position. Therefore, due to the limitation of data, the additional verification are necessary for the future study.

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