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- Technical Paper -

ANALYSIS OF CHLORIDE INGRESS INTO CONCRETE SUBJECTED TO AIRBORNE SALT MEASURED BY WIND TUNNEL TEST

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ABSTRACT

Chloride ingress into concrete subjected to airborne salt was investigated by a wind tunnel test. Time-dependent chloride profiles in concrete were experimentally obtained. Based on the obtained test results, surface chloride and diffusion coefficient of concrete were experimentally evaluated. The obtained surface chlorides are dependent of intensity of airborne salt. Several computational models were examined. The computational method in which variables surface chloride and diffusion coefficient are used can simulate well chloride profiles.

Keywords : airborne salt, chloride ingress, wind tunnel

1. INTRODUCTION

Chloride ingress into concrete is known as one of the most important factors affecting durability of concrete structures since it causes corrosion of steel reinforcement embedded in concrete. The sauces of chlorides in actual concrete structures are splash and tidal action of sea water, airborne salt from the sea, deicing agent and initially induced chloride with sea sand. In this paper, airborne salt which dominates service life of coastal concrete structures is focused. According to the Standard Specification for Concrete Structures by JSCE (Japan Society of Civil Engineers), the time when chloride content at the reinforcing bar portion in concrete reaches the designated threshold value is defined as one of the limit states of structural durability [1]. The time-dependent chloride content in concrete is calculated by Fick's diffusion equation, in which empirically determined surface chloride content is used as a boundary condition, depending on distance from the shore line.

In order to improve the accuracy in service-life prediction of concrete structures, it is necessary to adequately estimate surface chloride content taking into account airborne salt arriving to concrete surface as well as diffusion coefficient in concrete. Surface chloride and diffusion coefficient have been investigated in many previous studies. However, most previous studies on relationship between environmental conditions and chloride ingress into concrete are based on field data which might be affected various factors such as uncertainly changing in local climate, effect of rainfall and long-term change of concrete properties. It has been, therefore, difficult to evaluate pure relationship between airborne salt and chloride ingress into concrete, which should be necessary to calibrate and verify computational models. Moreover, it takes long time to obtain time-dependent experimental chloride profiles in concrete by exposure test under actual coastal environment.

Then, a new laboratory test method for chloride ingress into concrete subjected to airborne salt is developed by the authors' research group [2]. Artificially controlled airborne salt is produced in the wind tunnel. Concrete specimens are continuously exposed to airborne salt under the controlled environment. In this paper, relationship between intensity of airborne salt and surface chloride content is investigated based on the test results obtained by the developed testing equipment. Diffusion coefficient derived from the obtained chloride profile is also discussed.

2. EXPERIMENTAL METHOD

2.1 Wind Tunnel

Fig. 1 shows the outline of the wind tunnel, in which coastal environment involving airborne salt is simulated. Its inside views are shown in Fig. 2. Fig. 3 shows the overview of the wind tunnel. The size of the cross section inside of the wind tunnel is 1 m x 1 m. The length of wind path is about 12 m in one round. Particles of salt water are produced by putting fine air bubbles into the salt water unit (Fig. 2(b)) and blown by the fan (Fig. 2(a)). Concrete specimens are set in both the first and the second floor and exposed to wind involving airborne salt (Fig. 2(c)). Wind velocity and amount of airborne salt at installation position of each specimen in the wind tunnel were measured prior to the exposure test. Wind velocity was measured by a portable wind velocity meter. The measured wind velocity in the tunnel was 1.5 m/s in average. The amount of airborne salt at each specimen's position was measured by a gauze specimen whose size is 100 mm x 100 mm (Fig. 2(d)). Gauze specimens are exposed at the testing position for four hours to catch airborne salt.

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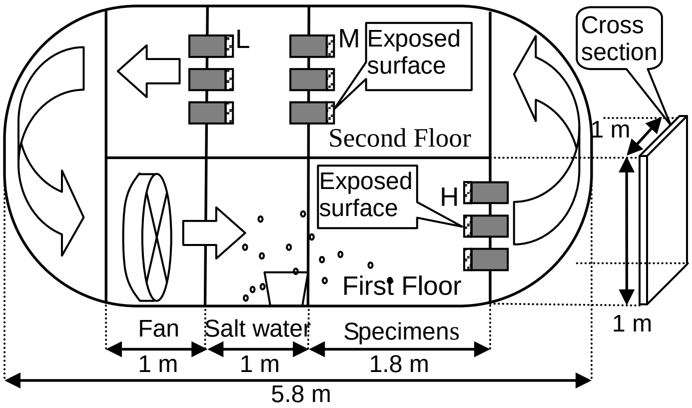

Fig.1 Outline of the wind tunnel and installation position of specimens

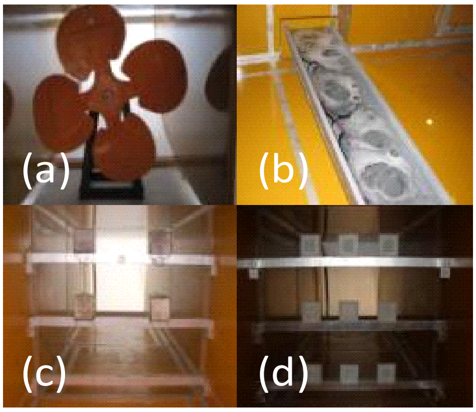

Fig.2 Inside views of the wind tunnel
(a) Fan, (b) salt water unit, (c) exposed specimens and (d) gauze catching airborne salt

Fig. 3 The outside overview of the wind tunnel

The amount of airborne salt per unit area per unit time was indicated by the unit of mdd (mg/dm^2/day).

2.2 Specimen

Concrete specimens whose size is 100 x 100 x 150 mm were used. Two types of concrete mix whose water cement ratio is 40% and 60% were used, as shown in Table 1. Specimens were cured in water for 28 days. However, concrete strength was not measured. After curing, five surfaces of each specimen except one exposed surface were coated with tar epoxy to ensure one-dimensional chloride ingress into concrete from the exposed surface, as shown in Fig. 4.

Table 1 Concrete mixture

No	*w/c* (%)	*s/a* (%)	(kg/m^3) W	C	S	G	Ad. (g)
1.	40	41	159	398	712	1047	3.98
2.	60	45	165	275	820	1025	2.75

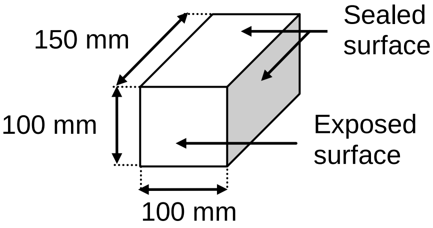

Fig. 4 Concrete specimen

2.3 Exposure Test

Specimen H-40 and H-60 were tested in the first floor of the wind tunnel to be exposed to high intensity of airborne salt (68.2 mdd), while specimens M-40, M-60 were exposed to moderate airborne salt (15.2 mdd), L-40 and L-60 were low airborne salt (5 mdd) in the second floor. In the first floor, intensity of airborne salt at the lower installation position is higher in comparison with middle or upper installation position. However, in the second floor the intensity of airborne salt is almost uniform everywhere. This fact suggests that particle size of salt water blown in the second floor is fine enough to be free from gravity. During the exposure test, specimens were taken out from the wind tunnel when chloride contents in concrete were measured. After measurement, specimens were exposed again.

2.4 Measurement of Chloride Content in Concrete

To measure chloride content in concrete, samples of concrete powder were taken from the specimen by drill at 100 mm, 200 mm, and 400 mm from the exposed surface. Chloride content in concrete was measured by a chloride ion meter. The procedure for measurement is shown in Fig. 5.

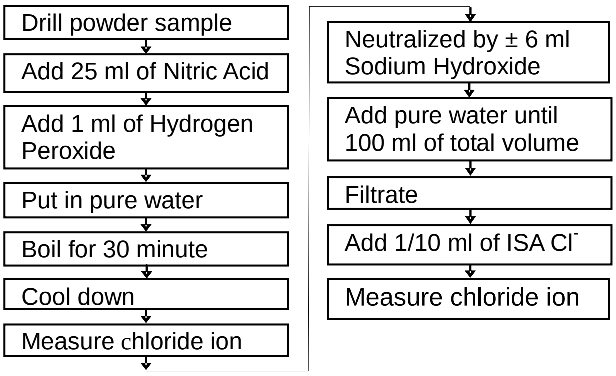

Fig. 5 Procedure of measurement of chloride ion

3. TEST RESULTS

Fig. 6 shows time-dependent profiles of chloride contents in the specimens. Since there was no measurement data on initial chloride content in concrete before the exposure, the average chloride content on 12 days were used as initial chloride content. Hence, adjusted chloride ingress into concrete at each exposure time was calculated by drawing the initial value from the measured absolute chloride content. Chloride content in concrete during exposure increased with increasing of exposure time at every portion of all the specimens. Increasing of chloride content near the surface is greater than those in the deeper portion.

It is regarded that chloride ingress into concrete is affected by the intensity of airborne salt. Comparing specimens made of same concrete mixture, chloride ingress is accelerated by the intensity of airborne salt to which the specimen is continuously exposed. Part of the airborne salt which reached the surface of concrete was caught and gradually penetrated into concrete by diffusion mechanism. It is supposed that the amount of airborne salt caught by concrete surface is dependent of the intensity of airborne salt.

4. ANALYTICAL METHOD

Transport process of chloride within concrete shown in Eq.(1) is estimated by one-dimensional diffusion model.

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \qquad (1)$$

where C = chloride content in concrete (kg/m^3); t = time from the starting of exposure (day); x = depth from the exposed surface (mm); D = diffusion coefficient (m^2/ s)

The fixed boundary condition model is adopted here. Chloride content in concrete at the exposed boundary surface is given in terms of surface chloride content C_0 as shown in Eq.(2).

$$\text{at } x = 0: C(0,t) = C_0 \qquad (2)$$

Constant and time-dependent surface chloride contents and diffusion coefficient are derived from experimental results of time-dependent chloride profiles.

Using the obtained surface chloride and diffusion coefficient, chloride ingress process is calculated again in section 5.3. Combination of surface chloride model and diffusion coefficient model are shown in Table 2.

Table 2 Combinations of surface chloride and diffusion coefficient in section 5.3

Method	Boundary Condition	Diffusion Coefficient
1	$C(x = 0) = C_0$	D_1 (derived from mean C_0)
2	$C(x = 0) = C_0$	$D_1(t)$ (derived from mean C_0)
3	$C(x = 0) = C_0(t)$	$D_2(t)$ (derived from $C_0(t)$)
4	$C(x = 0) = C_0(t)$	D_2 (derived from $C_0(t)$)

4.1 Determination of Surface Chloride Content

The surface chloride content is determined from the experimental results according to following procedure.

(1) Plot inner chloride profile in concrete at time t_j using the experimental results as shown in Fig. 7.

(2) Estimate the surface chloride content at time t_j by extrapolating the experimental inner chloride profile as shown in Eq.(3) and Fig. 7.

$$C(x) = \sum_{i=1}^{N} C(x_i)\, P_i^L(x) \qquad (3)$$

where $C(x_i)$ = the known values of inner chloride content (kg/m^3); $C(x)$ = the desired value of chloride content, by means of surface chloride content at x = 0; P_i^L = Lagrange polynomial of order N - 1

(3) Using the several number of obtained $C_0(t_j)$, draw a regression curve of $C_0(t)$, which can be used as time-dependent surface chloride content $C_0(t)$, as shown in Eq. (4) and Fig. 8.

$$C_0(t) = a\,(1 - e^{-bt}) \qquad (4)$$

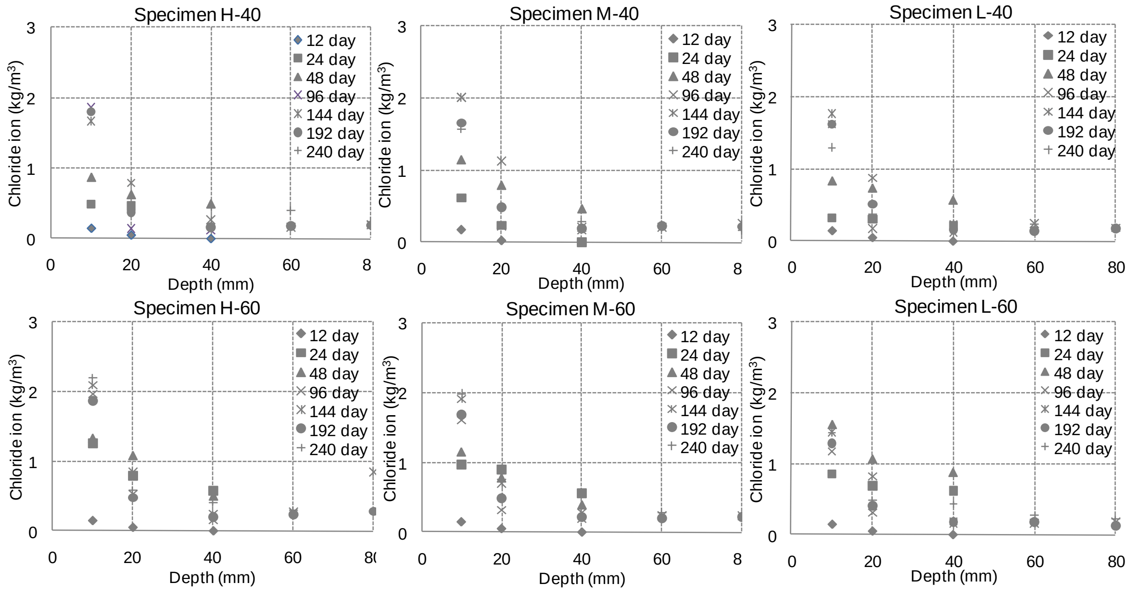

Fig. 6 Experimental time-dependent profiles of chloride contents in concrete

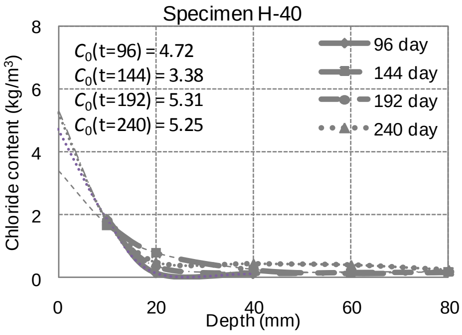

Fig. 7 Extrapolated surface chloride content from inner chloride content in specimen H-40

where *a* and *b* are parameters for time-dependent surface chloride content, which are determined by least square method.

(4) Mean surface chloride is calculated by averaging $C_0(t)$ with respect to time, as shown in Eq.(5).

$$C_0 = \frac{1}{T}\int_0^T C_0(t)dt \tag{5}$$

where T is time of exposure (day)

4.2 Determination of Diffusion Coefficient

Diffusion coefficient is determined using analytical solution for diffusion equation under fixed boundary condition according to following procedure:

(1) The solution of diffusion equation in semi-infinite body under fixed boundary condition is used in Eq.(6)

$$C(x,t) = C_0\left\{1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right\} \tag{6}$$

(2) Transforming Eq.(6), diffusion coefficient is obtained as shown in Eq.(7).

$$D(x,t) = \frac{1}{t\left\{\frac{2}{x}erf^{-1}\left(1-\frac{C(x,t)}{C_0}\right)\right\}^2} \tag{7}$$

where $C(x,t)$ is experimentally obtained chloride content in concrete, C_0 is mean surface chloride content obtained by extrapolation method as explained in 4.1. Either mean or time-dependent surface chloride content is used in Eq.(7).

(3) Obtained diffusion coefficient D at each x and t is averaged with respect to position, shown in Eq.(8).

$$D(t) = \frac{1}{X}\int_0^X D(x_i, t_j)dx \tag{8}$$

where $D(\mathbf{x}_i, \mathbf{t}_j)$ = chloride diffusion coefficient with respect to position and time (m^2/s); X = depth of specimen (mm)

Thereafter, regression curve for time-dependent diffusion coefficient *D(t)* expressed by Eq.(9) is adopted.

$$D(t) = c\ t^{-d} \tag{9}$$

where *c* and *d* are parameters for time-dependent diffusion coefficient.

(4) Mean diffusion coefficient is calculated by averaging *D(t)* with respect to time, as shown in Eq. (10).

$$D = \frac{1}{T}\int_0^T D(t)dt \tag{10}$$

In numerical simulation in 5.3, diffusion coefficient calculated from mean surface chloride C_0 is used in calculating chloride profiles under constant surface chloride content C_0 as boundary condition, while diffusion coefficient calculated from variable surface chloride $C_0(t)$ is used in calculating chloride profiles under time-dependent surface chloride as boundary condition.

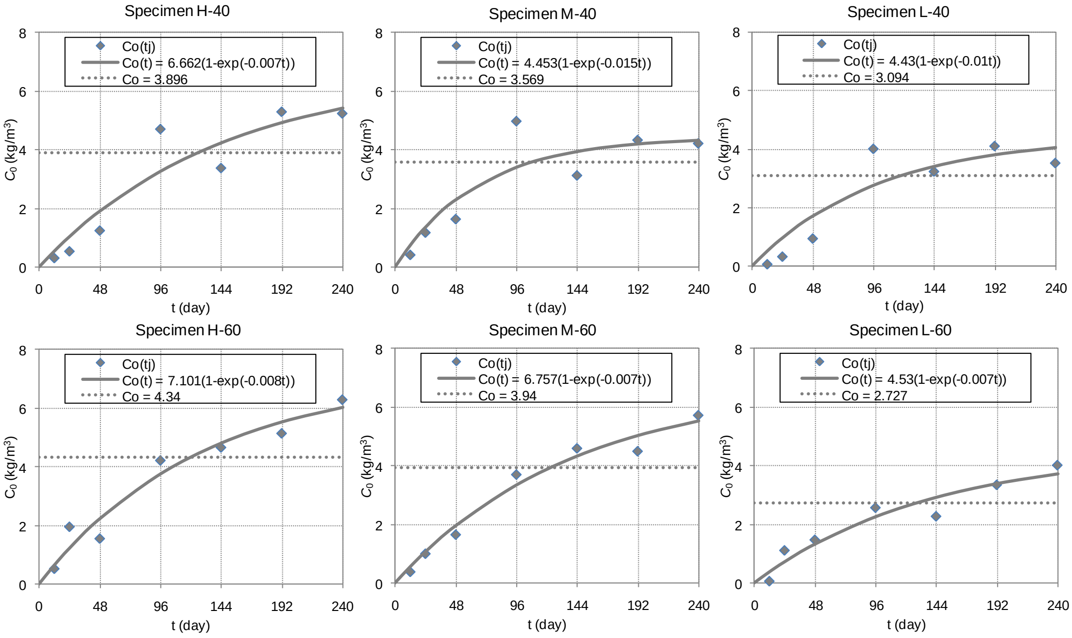

Fig. 8 Time-dependent and mean surface chloride contents

5. ANALYTICAL RESULTS AND DISCUSSION

5.1 Surface Chloride

The obtained mean surface chloride content of all specimens and their intensity of airborne salt are shown in Table 3 and Fig. 9. Furthermore, relationship between airborne salt and both mean and time-dependent surface chloride in all specimens is shown in Table 3. According to Fig. 8, the dependency of surface chloride on the intensity of airborne salt is found in both series of w/c 40% and 60%. However, the difference in C_0 is not remarkable compared with the difference in C_{air}.

In general, smaller w/c results in larger C_0. According to Table 3, H and M series show the adverse tendency. The reason of this is not clear at this moment.

Table 3 Mean and time-dependent surface chloride

Series	C_{air} (mdd)	w/c	Mean C_0 (kg/m^3)	C_0(t) (kg/m^3)
H-40	60.6	40	3.90	$6.66(1-e^{-0.007t})$
M-40	14.7	40	3.57	$4.45(1-e^{-0.015t})$
L-40	4.9	40	3.09	$4.43(1-e^{-0.01t})$
H-60	68.2	60	4.34	$7.10(1-e^{-0.008t})$
M-60	15.2	60	3.94	$6.76(1-e^{-0.007t})$
L-60	5.0	60	2.73	$4.53(1-e^{-0.007t})$

mdd = mg/dm^2/day

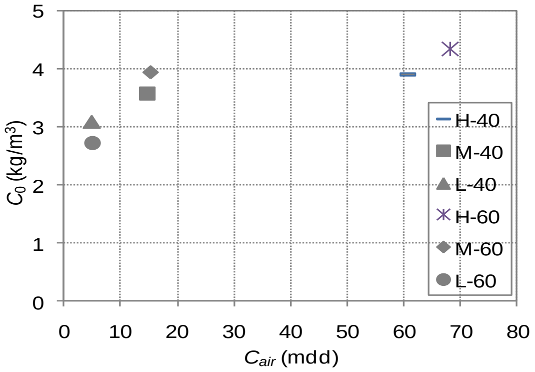

Fig. 9 Relationship between intensity of airborne salt and surface chloride content

5.2 Diffusion Coefficient

Diffusion coefficient is derived under either mean or time-dependent surface chloride, as shown in Fig. 11. The calculation results are shown in Table 4. Diffusion coefficient $D_2(t)$, which are derived under time-dependent surface chloride, decreases with increasing of time. Diffusion coefficient $D_1(t)$, which are derived under mean surface chloride, does not much change with respect to time. Correlation of w/c and diffusion coefficient D_1, which are derived under mean surface chloride, in all specimens is shown in Fig. 10. It can be verified that the obtained diffusion coefficient of concrete with lower w/c is smaller than that with high w/c.

5.3 Numerical Simulation of Chloride Ingress into Concrete Subjected to Airborne Salt

The analytical solution for diffusion equation with error-function is used for re-calculation of chloride profiles. In fact, chloride profiles in all specimens are calculated. There is, however, no significant difference in qualitative tendencies in calculation results among specimens. Therefore, calculated result of time-dependent chloride profiles of only one specimen, H-40, is shown in Fig. 12. The tendencies between experimental and analytical results are reasonable.

Table 4 Mean and time-dependent diffusion coefficient

Series	Diffusion coefficient (m^2/s)			
	$D_1(t)$ based on C_0	Mean D_1 based on C_0	$D_2(t)$ based on $C_0(t)$	Mean D_2 based on $C_0(t)$
H-40	5E-11t$^{-0.184}$	2.29E-11	1E-09t$^{-0.99}$	2.82E-11
M-40	7E-11t$^{-0.265}$	2.59E-11	5E-10t$^{-0.714}$	2.78E-11
L-40	3E-11t$^{-0.061}$	2.70E-11	4E-10t$^{-0.685}$	3.66E-11
H-60	1E-10t$^{-0.321}$	3.35E-11	2E-09t$^{-1.005}$	4.21E-11
M-60	2E-10t$^{-0.399}$	2.88E-11	1E-08t$^{-1.347}$	2.52E-11
L-60	4E-10t$^{-0.581}$	3.86E-11	8E-09t$^{-1.315}$	6.94E-11

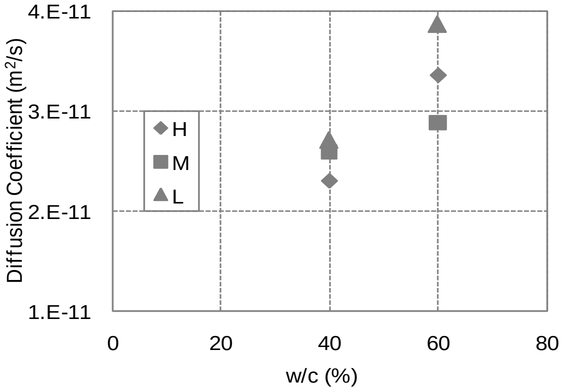

Fig. 10 Relationship between w/c and mean diffusion coefficient

The analytical results of time-dependent chloride profiles by method 1, in which constant surface chloride and constant diffusion coefficient were used, are shown in the first graph in Fig. 12. The analytical results well agree with experimental data up to 96 day. However, method 1 overestimates experimental results in longer time. This is because averaged diffusion coefficient becomes greater than variable one in longer time.

The analytical chloride profiles in the second graph in Fig. 12 show results by method 2, in which constant surface chloride content and time-dependent diffusion coefficient were used. The analytical results agree with experimental ones better than method 1 even in longer time.

The analytical chloride profiles in the third graph in Fig. 12 show results by method 3, in which time-dependent surface chloride and time-dependent diffusion coefficient were used. The analytical results well simulate experimental chloride profiles in both shorter and longer time.

The analytical chloride profiles in the last graph in Fig. 12 show results by method 4, in which time-dependent surface chloride and constant diffusion coefficient were used. The analysis estimates well experimental results in shorter time, but overestimates them in longer time more than method 1. It is because averaged diffusion coefficient in method 4 is greater than that in method 1.

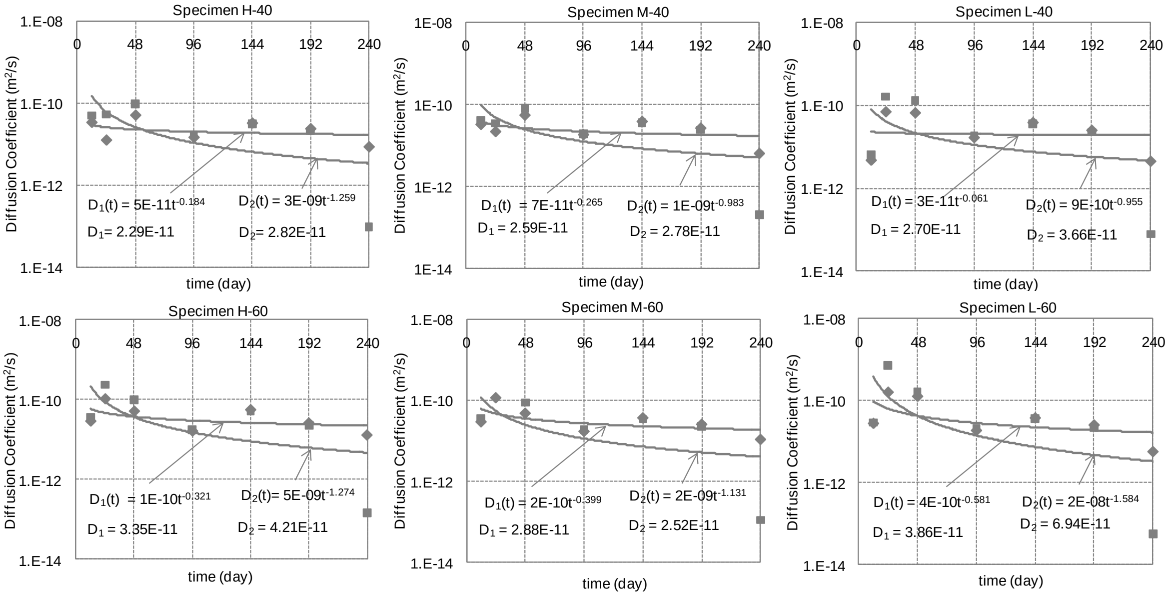

Fig. 11 Time-dependent and mean diffusion coefficient derived based on mean C_0 ($D_1(t)$, D_1), and those derived based on $C_0(t)$ ($D_2(t)$, D_2)

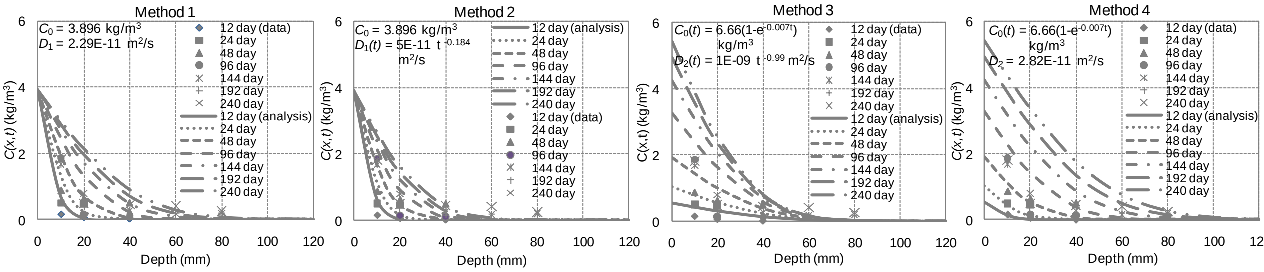

Fig. 12 Calculated time-dependent chloride profiles in specimen H-40

The tendency discussed above is natural because both surface chloride and diffusion coefficient used here had been derived from the experimental data used in the verification. It is necessary, therefore, to verify the applicability of surface chloride and diffusion coefficient obtained by the laboratory test to chloride ingress in actual structure under real environment in further study.

6. CONCLUSIONS

Following conclusions were obtained from the conducted experiment and analysis.

(1) Time-dependent chloride profile in concrete subjected to airborne salt can be obtained by the developed wind tunnel test.

(2) The obtained surface chloride content of concrete is dependent of the intensity of airborne salt.

(3) The obtained diffusion coefficient of concrete with low water cement ratio is relatively smaller than that with high water cement ratio.

(4) Chloride ingress analysis based on constant diffusion coefficient overestimates long term chloride content in concrete.

(5) Chloride ingress analysis based on time-dependent diffusion coefficient can estimate long term chloride profiles better than constant diffusion coefficient.

(6) Chloride ingress analysis based on time-dependent surface chloride as boundary condition can better estimate chloride profiles in early stage than constant surface chloride.

(7) Chloride ingress analysis based on time-dependent diffusion coefficient and time-dependent surface chloride can well estimate both short and long term chloride profiles.

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