INVESTIGATION ON EXPERIMENTAL SURFACE CHLORIDE CONCENTRATION IN CONCRETE

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ABSTRACT

Surface chloride of concrete as boundary condition is investigated based on the exposure test results obtained by the wind tunnel. Specimens are continuously exposed to controlled airborne salt in the wind tunnel. Several types of boundary condition model are examined based on the obtained experimental results. The dependency of surface chloride on airborne salt and water cement ratio is investigated. Laboratory test on chloride ingress into concrete subjected to airborne salt is carried out by means of the original wind tunnel. The result shows that surface chloride is dependent of intensity of airborne salt. The dependency of surface chloride content on water cement ratio is not clear. Mean surface chloride determined from short-term exposure test underestimates long-term chloride ingress into concrete.

Key words: airborne salt, concrete, surface chloride concentration, water-cement ratio, wind tunnel

INTRODUCTION

In order to solve diffusion equation for chloride transport in concrete, Fick's second law, initial and boundary condition are necessary. Initial condition is the distribution of chloride content in concrete when exposure starts. In this paper, boundary condition is focused. The purpose of the investigation of parameters based on short-term data is to know the necessary length of exposure to estimate long-term chloride ingress adequately.

Calculated chloride concentration near the concrete surface is influenced by the type of boundary condition used in calculation. When time-dependent surface chloride is adopted as boundary condition, chloride concentration near the concrete surface will vary with time. On the other hand, it will be constant value when constant surface chloride content is adopted.

In this paper, constant surface chloride content C_0 and time-dependent surface chloride content $C_0(t)$ are extracted from the results of the wind tunnel test (Nuralinah, D., 2011). Natural type of boundary condition based on an analogy with heat transfer phenomena is also adopted.

EXPERIMENTAL METHOD

Figure 1 and **Figure 2** show the wind tunnel which simulates coastal environment involving airborne salt in the laboratory. The cross section size inside of the wind tunnel is 1 m x 1 m. The wind path length is about 12 m in one round. Air flow is generated by a propeller driven by electric motor. Particles of salt water are produced by putting fine air bubbles into the salt water bath. Concrete specimens are set and exposed to airborne salt in both the first and the second floor in the wind tunnel. Averaged wind velocity in the tunnel was 1.5 m/s. The measured airborne salt per unit area per unit time was 5 to 68.2 mdd (mg/dm^2/day), which depends on the testing position in the wind tunnel. Value of airborne salt is expressed in terms of amount of Natrium Chloride.

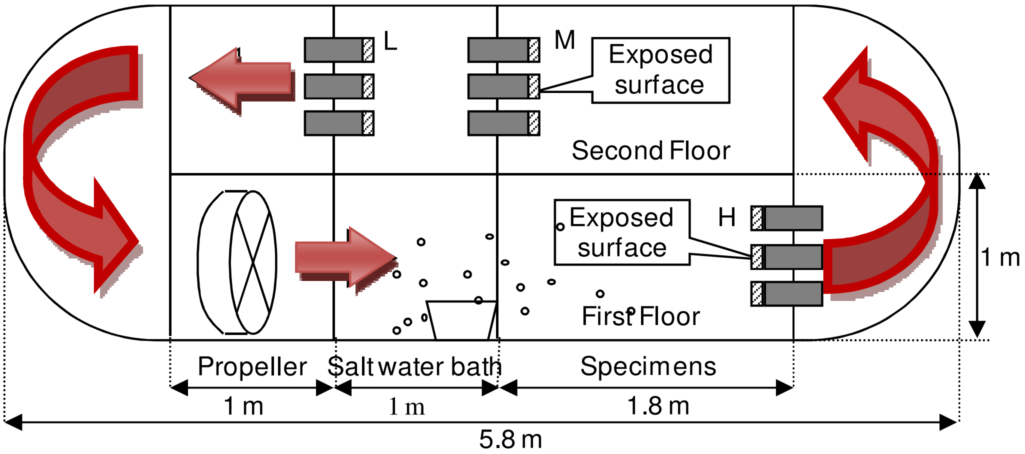

Figure 1. Outline of The Wind Tunnel

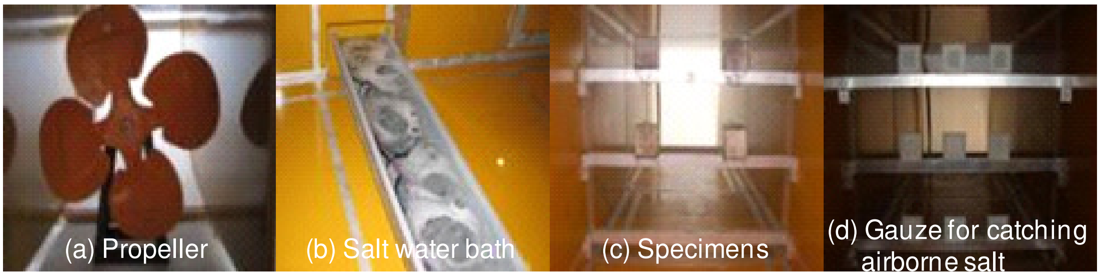

Figure 2. Inside Views of The Wind Tunnel

Concrete specimen used in the exposure test is shown in **Figure 3**. Two types of concrete mix whose water-cement ratio is 40% and 60% were used. Specimens were cured in water for 28 days. 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. Six specimens in **Table 1** were tested. During the exposure test, specimens were taken out from the wind tunnel periodically and chloride content was measured by sampling concrete powder with drill from the specimens. Value of chloride content in concrete is expressed in terms of amount of chloride ion per unit volume. After measurement of chloride content, specimens were exposed again in the wind tunnel (Nuralinah, D., 2012).

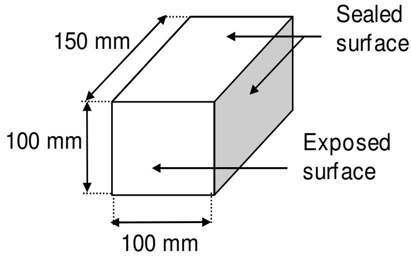

Figure 3. Concrete Specimen

Table 1. Test Condition of Specimens

Specimen	*W/C* (%)	Airborne salt (mdd)	Installation position
H-40	40	60.6	1st floor
M-40	40	14.7	2nd floor
L-40	40	4.9	2nd floor
H-60	60	68.2	1st floor
M-60	60	15.2	2nd floor
L-60	60	5	2nd floor

DETERMINATION METHOD OF EXPERIMENTAL SURFACE CHLORIDE

Figure 4 shows experimental time-dependent profiles of chloride contents in all specimens obtained by the wind tunnel test during 240 days of exposure. Based on these results, surface chloride content is determined by following procedure.

Surface chloride content is determined from the wind tunnel test results according to following procedure.

a) Surface chloride content at time t_j is estimated by extrapolating the experimental inner chloride profile by Lagrange polynomial in Eq.1. **Figure 5** shows the results of specimen H-40 for example.

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

where,
$C(x_i)$: known values of inner chloride content (kg/m^3);
$C(x)$: the approximated value of chloride content at x;
P_i^L : Lagrange polynomial of order N - 1. The surface chloride is estimated by setting $x = 0$.

b) The obtained surface chloride content $C_0(t_j)$ at the sampling time t_j is plotted as a function of time. Then, time-dependent surface chloride content $C_0(t)$ is simulated by a regression curve expressed by Eq. 2.

$$C_0(t) = a(1 - e^{-bt}) \qquad \text{....................} \quad (2)$$

where;
a, b : parameters for time-dependent surface chloride content determined by least square method.

Parameter a in Eq. 2 represents an extrapolated surface chloride after a long exposing time. Parameter a is also adopted as C_{ext}, an equivalent chloride concentration in concrete under the given environment in the natural type of boundary condition model, in which the mass flux of chloride through the exposed boundary surface (Nishi, T., 1999) is expressed as Eq. 3.

$$J = \alpha(C(0,t) - C_{ext}) \qquad \text{....................} \quad (3)$$

where,
J : mass flux of chloride through the boundary surface (kg/m^2/s);
α : experimental coefficient for surface transfer rate (m/s);
C_{ext} : equivalent chloride concentration in concrete under the given environment (kg/m^3).

The coefficient α specifies the magnitude of mass flux of chlorides throught the surface similarly with a heat transfer coefficient. The equivalent chloride concentration in concrete C_{ext} will be dependent of the intensity of arriving airborne salt, removal of surface chlorides by rainfall or splash and properties of concrete.

c) Mean surface chloride during the exposure period is mathematically calculated by averaging $C_0(t_j)$ with respect to time by Eq. 4.

$$C_0 = \frac{1}{T}\sum_{0}^{T} C_0(t_j)\,\Delta t_j \qquad \text{...................} \quad (4)$$

where,
T : length of time of exposure (day)
$C_0(t_j)$: experimental time-dependent surface chloride content.

The procedure for determination of surface chloride is summarized in summarized in **Figure 6.**

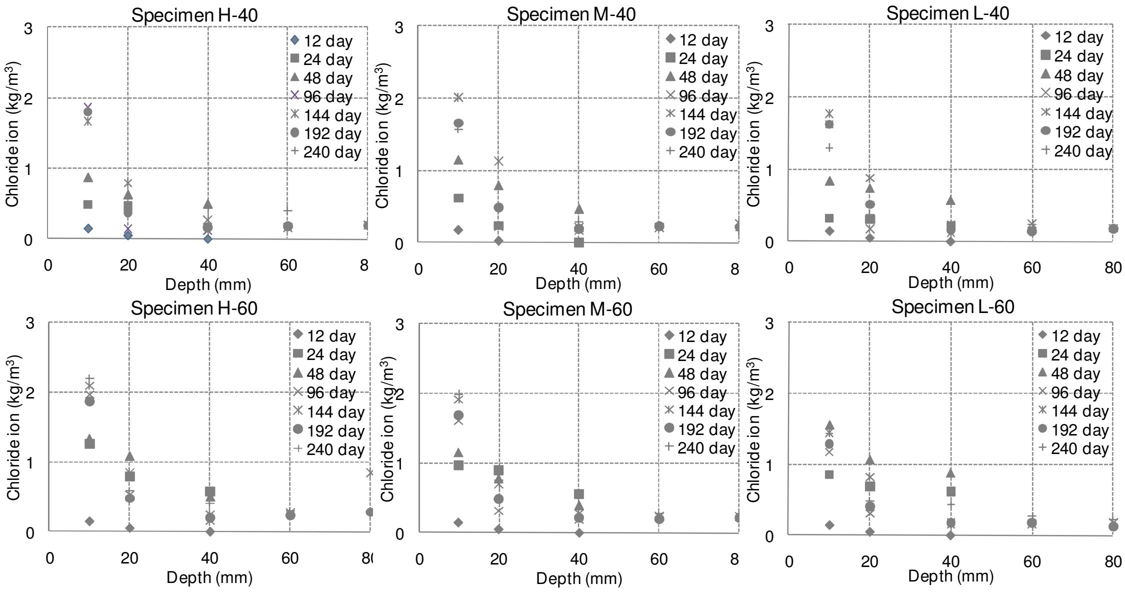

Figure 4. Experimental Time-Dependent Profiles of Chloride Contents in Concrete

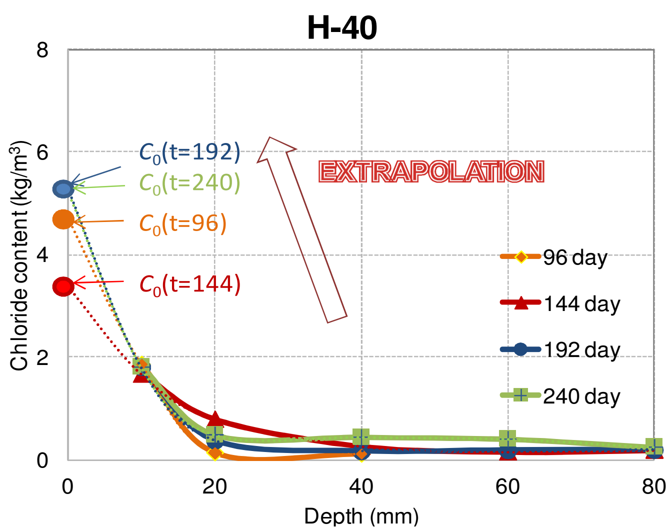

Figure 5. Extrapolated Surface Chloride Content From Inner Chloride Content in Specimen H-40

RESULT AND DISCUSSION

Surface chloride contents determined from data of 0-240 day

The obtained surface chloride content $C_0(t_j)$ of all specimens as a function of sampling time is plotted in **Figure 7.** Regression curves of time-dependent surface chloride content $C_0(t)$ by Eq. (3.2) are also drawn in **Figure 7.** It is regarded in **Figure 7** that the surface chloride increases with increasing of exposure time and approaches to a certain value in all cases.

The time-dependent surface chlorides of all specimens are shown in **Figure 8** and **Table 2.** Time-dependent surface chloride of specimen with high water-cement ratio is relatively greater than those of specimen with low water-cement ratio.

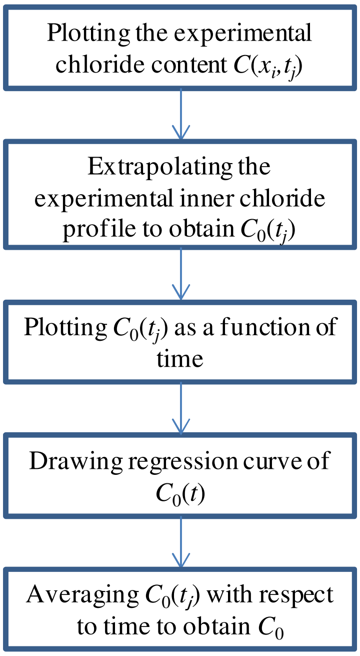

Figure 6. The Procedure of Determination of Surface Chloride

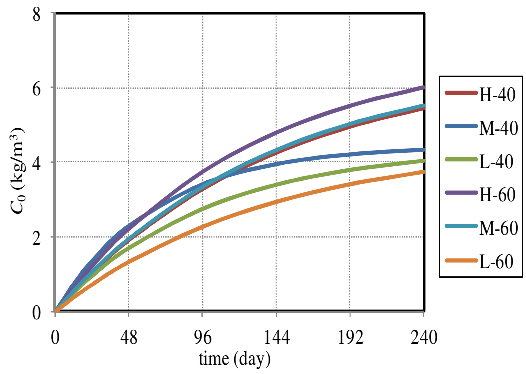

Figure 8. Time-Dependent and Mean Surface Chloride Contents of All Specimens Derived From 0-240 Day Data

Table 2. Mean and Time-Dependent Surface Chloride Content

Speci men	C_{air} (mdd)	W/C (%)	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

Figure 9 shows relationship between the mean surface chloride and the intensity of airborne salt. The mean surface chloride depends on the intensity of airborne salt in both series of 40% and 60% *W/C*. However, the difference of the mean surface chloride between the results in the series of 40% and 60% *W/C* is not evident. There is no clear dependency of mean surface chloride on water-cement of concrete in the experimental results in this study.

There are some previous studies by other researchers which report that surface chloride concentration is affected by properties of concrete in accordance with water-cement ratio. This fact suggests that surface chloride is influenced by concrete porosity and characteristics of chloride binding (Yuan Q., et. al., 1999). According to previous studies, smaller *W/C* results in greater surface chloride C_0 under the same condition of airborne salt. However, the difference according to W/C in **Figure 9** is too small to discuss the trend. Surface chloride slightly increases with increasing of the intensity of airborne salt in both water-cement ratio series.

Figure 10 shows relationship between apparent external chloride, which is estimated ultimate surface chloride, and intensity of airborne salt. It is regarded that apparent external chloride depends on the intensity of airborne salt in both water-cement ratio series. The dependency of apparent external chloride on water-cement ratio is not clear.

It is can be concluded that both surface chloride and apparent external chloride in the results in this study can be regarded as environmental condition independent from material properties. It is also confirmed that surface chloride is dependent of intensity of airborne salt.

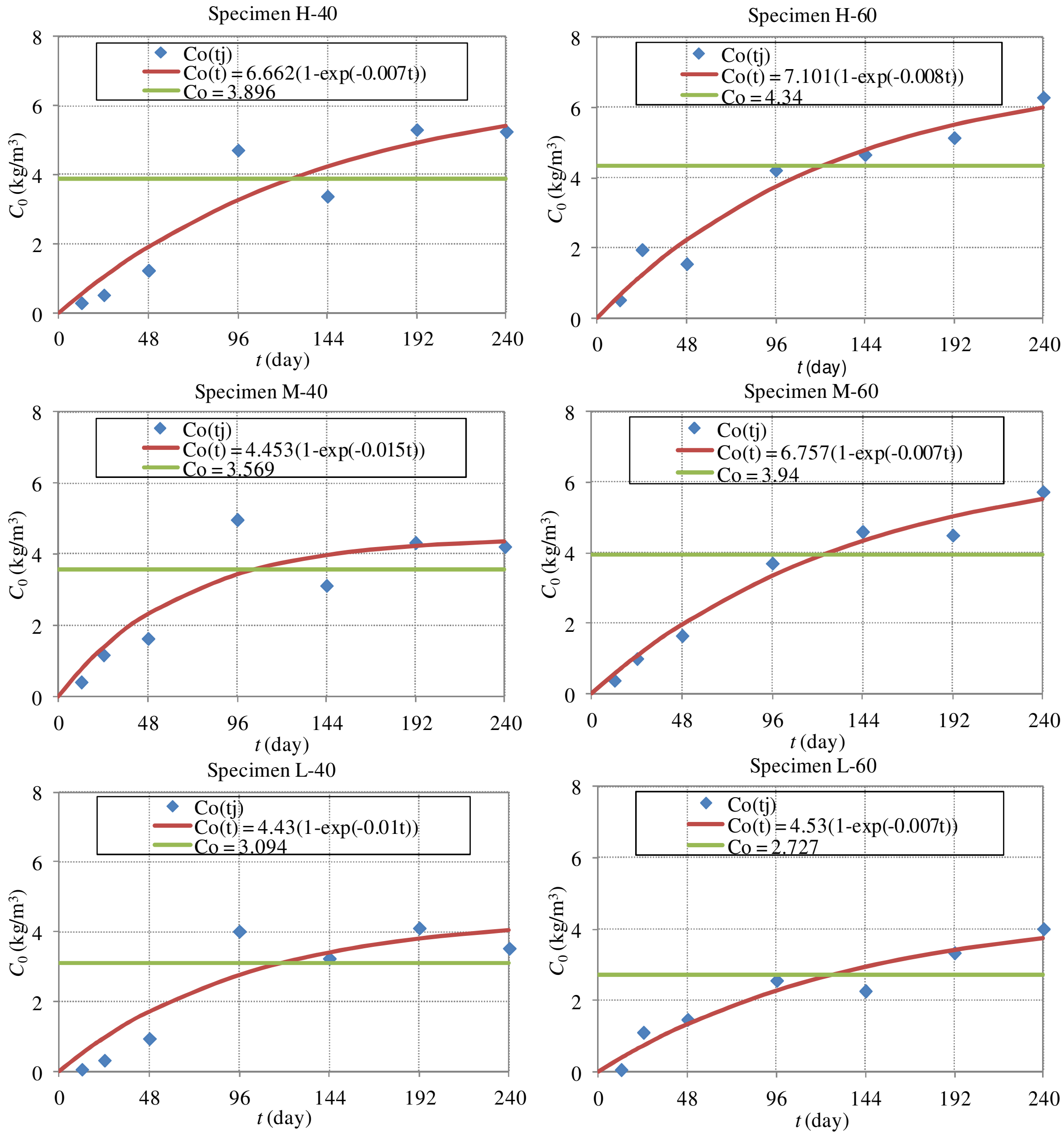

Figure 7. Time-Dependent and Mean Surface Chloride Contents of All Specimens Derived From 0-240 Day Data

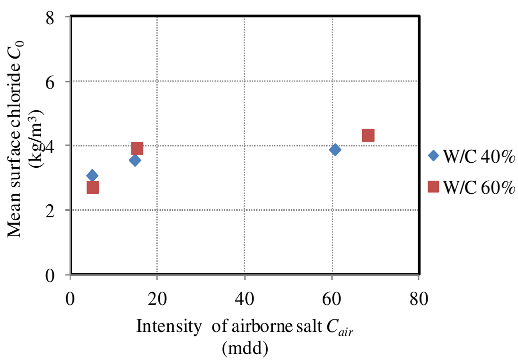

Figure 9. Relationship Between Intensity of Airborne Salt and Mean Surface Chloride Content of All Specimens Derived From 0-240 Day Data

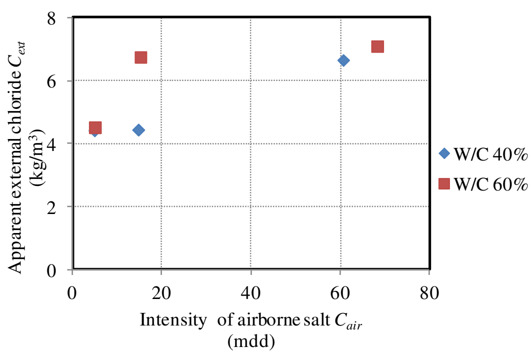

Figure 10. Relationship Between Intensity of Airborne Salt and Apparent External Chloride of All Specimens Derived From 0-240 Day Data

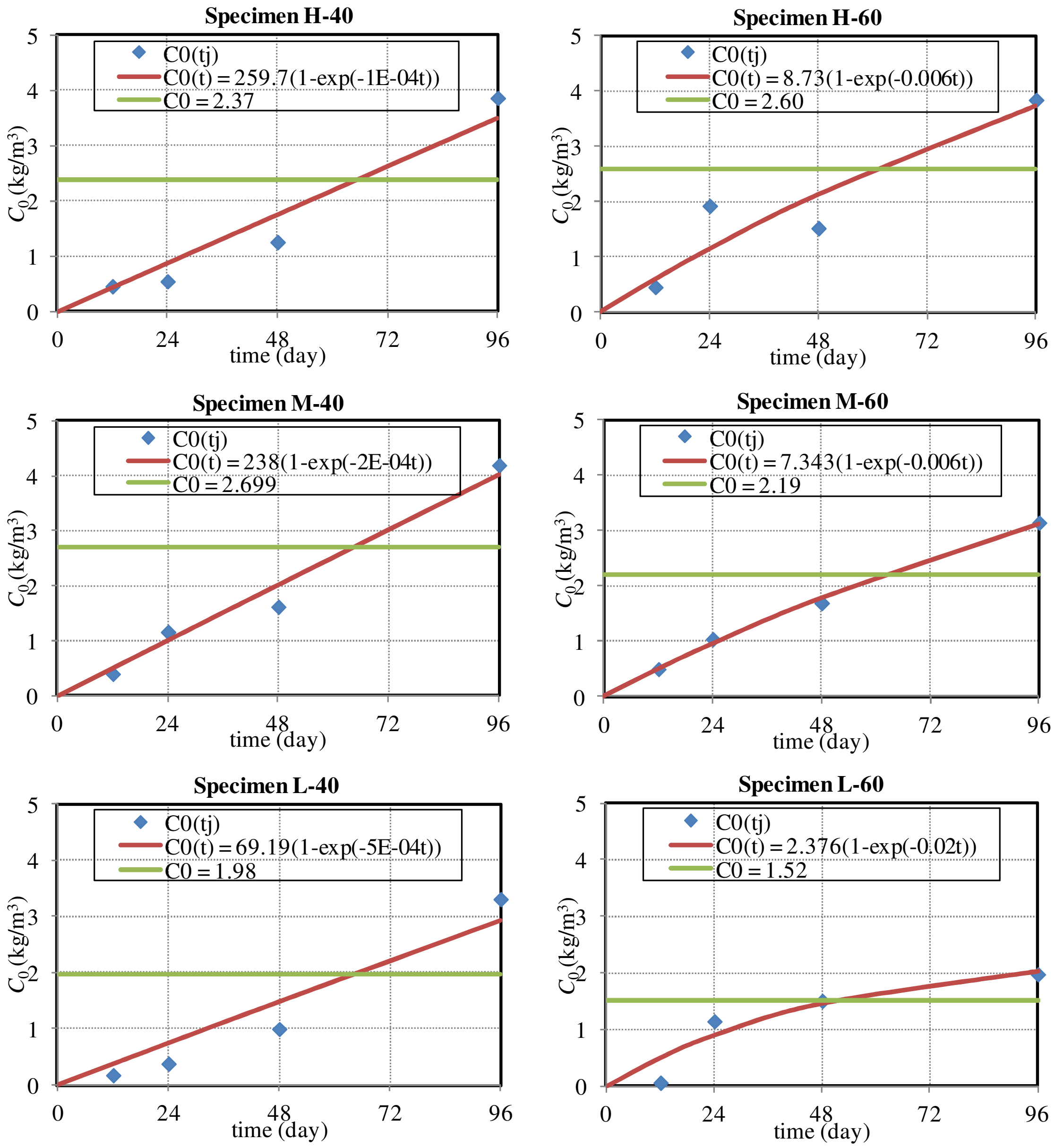

Figure 11. Time-Dependent and Mean Surface Chloride Contents of All Specimens Derived From 0-96 Day Data

Surface chloride determined from short-term data of 0-96 day

In this study, surface chloride contents is also determined from short-term data of 0-96 day and compared with those determined from long-term data of 0-240 day. Time-dependent and mean surface chloride contents of all specimens during 0-96 days are shown in **Figure 11** and **Table 3.** Regression curves of time-dependent surface chloride contents of all specimens derived from 0-96 day data are shown together in **Figure 12.** Regression curves of time-dependent surface chloride content in **Figure 12** are straighter and lower than those in **Figure 8.**

Different from the surface chloride determined from long-term data, the surface chloride determined from short-term data does not show the tendency that it approaches to a certain value. Therefore, the regression curve of time-dependent surface chloride may fail to estimate experimental results in long time. Relationship between the mean surface chloride and the intensity of airborne salt is shown in **Figure 13.** Though the general trend is similar with

Figure 9 based on long-term data, surface chloride determined from short-term data (0-96 day) is lower than that from 0-240 day data. It should be noted that mean surface chloride determined from short-term exposure test may cause underestimation of long-term chloride penetration if it is adopted in calculation as it is.

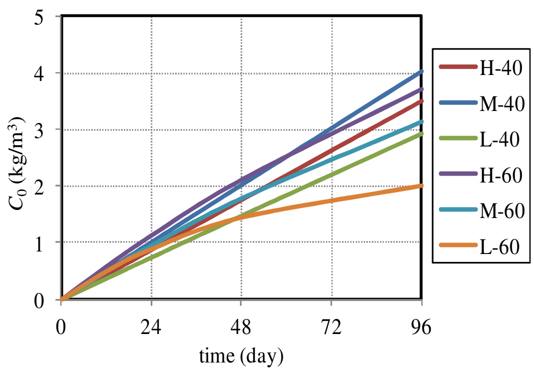

Figure 12. Time-Dependent Surface Chloride Contents of All Specimens Derived From 0-96 Day Data

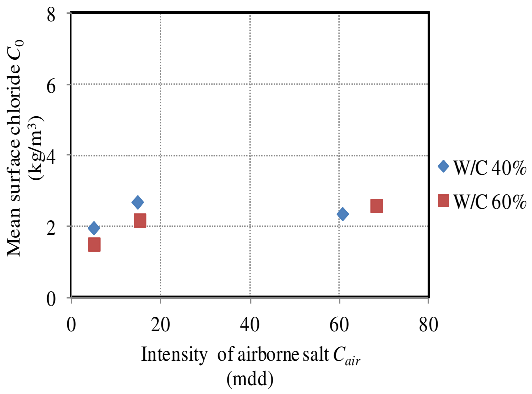

Figure 13. Relationship Between Intensity of Airborne Salt and Mean Surface Chloride of All Specimens Derived From 0-96 Day Data

Table 3. Mean and Time-Dependent Surface Chloride Conten

Specimen	C_{air} (mdd)	W/C (%)	C_0 (kg/m^3)	$C_0(t)$ (kg/m^3)
H-40	60.6	40	2.37	$259.7(1\text{-}e^{-1E\text{-}04t})$
M-40	14.7	40	2.70	$238(1\text{-}e^{-2E\text{-}04t})$
L-40	4.9	40	1.98	$69.19(1\text{-}e^{-5E\text{-}04t})$
H-60	68.2	60	2.60	$8.73(1\text{-}e^{-0.006t})$
M-60	15.2	60	2.19	$7.343(1\text{-}e^{-0.006t})$
L-60	5.0	60	1.52	$2.376(1\text{-}e^{-0.02t})$

mdd = mg/dm^2/day

CONCLUSION

Following conclusions were obtained concerning experimental surface chloride based on the wind tunnel test.

(1) Surface chloride increases with increasing of exposure time and approaches to a certain value.

(2) Mean surface chloride during the exposure is dependent of the intensity of airborne salt. Same trend is recognized in estimated ultimate surface chloride which is adopted as an apparent external chloride.

(3) Dependency of mean surface chloride on water-cement ratio is not clearly recognized in the results in this study. Therefore, surface chloride can be approximately regarded as environmental condition independent of concrete properties.

(4) Surface chloride obtained by short-term exposure test of 96 days is lower than that obtained by test of 240 days. Therefore, mean surface chloride determined from short-term exposure test may cause underestimation of long-term chloride penetration if it is adopted in calculation as it is.

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