

**Chloride Diffusivity of Self-Compacting Concrete
With Limestone Powder**

Supakit Swatekititham

ID. 1035011

A Thesis Submitted to
Kochi University of Technology
in Partial Fulfillment of The Requirements for
The Degree of Master of Engineering

Supervisor
Professor Hajime Okamura

Department of Infrastructure System Engineering
Kochi University of Technology
Kochi, Japan

January 2001

Acknowledgement

The intense appreciation would be presented to Prof. Hajime Okamura, Department of Infrastructure System Engineering, Kochi University of Technology, for his valuable suggestion, inspection and encouragement all the way through this study.

Thankfulness for the helpfulness of the references' investigation and solve a number of intricacies for the period of study would be rewarded to Prof. Hiroshi Shima, Assist. Prof. Masahiro Ouchi, and Mr. Masaru Ueno.

Grateful acknowledgement is extended to Prof. Mikio Kadota and Assoc. Prof. Toshio Yoshii for their interests and serving as members of examination committee.

Thanks for all Thai and Japanese friends at Kochi University of Technology for their heartfelt help to carry on the experiment to accomplish the target all over this study.

Abstract

This paper investigated on the chloride ion movement in self-compacting concrete. The empirical formulas for chloride diffusion coefficient, which is a function of water-to-cement ratio, can be examined differently from a conventional concrete. The mix proportions were separated into two types; self-compacting concrete and normal concrete blended with limestone powder. The soaking test and fogging test were done in order to match with the actual structures in the seawater and the seashore area, respectively. Bleeding was also taken into consideration of chloride content along the depth of a specimen. In this set of experiment, concrete blended with limestone powder showed the decrease of chloride diffusivity for the concrete of the same water-cement. Bleeding effect was shown the different of the chloride concentration at surface between top and bottom part of a specimen, which is concerned with many parameters. The concept of total chloride ion concentration at inner surface was formulated with time dependence, which can be obtained an appropriate value for the time of consideration.

Table of Contents

	Page
Acknowledgement	i
Abstract	ii
Table of contents	iii
List of tables	iv
List of figures	v
Chapter 1: Introduction	1-3
Chapter 2: Literature Review	4-9
- Modeling of chloride ion movement in the surface layer of hardened concrete	4
- The durability standard specification for concrete	5
- The investigation on minimum maintenance for prestressed concrete bridge	6-7
- An integrated computational system of mass/energy generation, transport and mechanics of materials and structures	8
- A Multicomponent composite porous medium	8-9
Chapter 3: Experimental Outline	10-12
Chapter 4: Experimental Results & Verification	
- Part 1: Total chloride ion concentration and diffusion coefficient	13-24
- Part 2: The analysis of chloride ion concentration at inside surface of concrete.	25-28
Chapter 5: Conclusion	29
Chapter 6: Further Study	30
References	31-32
Acknowledgement:	
Appendix A: Tables show the total chloride ion concentration of the specimens by varying type of concrete, time, w/c and type of testing	
Appendix B: Tables show the diffusion coefficient of concrete	
Appendix C: The aggregate gradation by sieve test	
Appendix D: The total chloride ion concentration at inner surface of concrete	
Appendix E: Verification data collected from the references	

List of Tables

	Page
Table 1. Mix proportion for chloride testing.	11
Table 2. Material Properties	11
Table 3. Properties of each mix proportion	11
Table 4: Void Curve	12
Table 5: A Mean Constant Diffusion Coefficients from Appendix B	25

List of Figures

	Page
Fig. 1: Condensation mechanism of chloride ions in the surface layer of concrete	4
Fig. 2: The relationship between the surface concentration and distance from seashore.	6
Fig. 3: The comparison of the total chloride concentration curves between previous assumption and this paper	7
Fig. 4: The diffusion coefficient against w/c curve	7
Fig. 5: The multicomponents of concrete	8
Fig. 6: Schematic representation of hard core soft shell model	9
Fig. 7: Computed percolation curves of a composite containing spherical, equally sized aggregate particles	9
Fig. 8: Void curve used in normal concrete design	12
Fig. 9-38: Total chloride ion concentration at time 1, 3 and 5 months of testing	15-23
Fig. 39-42: The average diffusion coefficients of concrete	24
Fig. 43: Comparison between 2 assumptions of chloride concentration at surface	26
Fig. 44-51: The total chloride ion concentration at the inner surface	27-28

Introduction

In recent times, the design of concrete structure is based on the structural performance and the environmental conditions. A performance-based design is a solution for new generation of design method. This design method is needed to supply for any requirement of structural performance in various environmental conditions. The performance-based design needs the durability index to take in the consideration. One of the main indexes is the deterioration of concrete structures by the corrosion of steel, which is affected by chloride ion penetration into concrete. The tests were held on the chloride ion movement in the various types of concrete using self-compacting concrete and normal concrete replaced by limestone powder. From the viewpoint of microscopic concept, different type of concrete provides a different hydration and microstructure development. The chloride transport through the depth from open surface of concrete is different. A structure standing on marine atmospheric zone has a different chloride penetration rate from another submerging in the seawater, thus the experiment had been done in two cases of soaking and fog tests for supporting those circumstances. For a beam structure, there is a bleeding effect in the longitudinal direction with the chloride penetration. By this phenomenon, the test was separated by the value of chloride content occurred along the depth from surface between top part and bottom part of specimens. It should be noted that the column structure would have the effect perpendicular to the chloride penetrating direction. Therefore this study does not apply to the column structure subjected to seawater; it's required a further study on that. Bleeding in a normal concrete is related to properties itself, such as w/c and water content and the applied force from vibration as well. The bleeding test cannot explain the behavior of the porosity distribution depending on the depth of a specimen. In the different way, self-compacting concrete was not required the vibration as applied in normal concrete, thus the behavior of porosity alignment may be guessed by a proper examination. In the case of limestone powder blended in concrete, the total chloride ion concentration is different from concrete without it. The reason is on the limestone powder acted as the filling material to the pore volume in concrete, especially interfacial zone. By the microstructure concept, compared concrete with limestone powder and without limestone powder at the same w/c, the diffusion in the case of no limestone powder will be higher than that with limestone powder. The diffusion coefficients in limestone powder blended with cement subjected to the chloride ion solution can be solved by this experiment. The reason is explained by aggregate influence in chapter 2 that limestone powder was assumed to be non-reactive material, even though it can be reacted in a little amount. Once we assumed it as aggregate portion in concrete, both of coarse and fine aggregates is affected on the interfacial pore volume and size. The exception is on a very fine aggregate as cement particle, which does not produce such effects on the interfacial zone [15], and also act as filler on the porosity in the interfacial zone. The fineness of limestone powder is very high so it can have very large contacted surface with water. Limestone powder resists the water move up by segregation and bleeding by the surface tension or adsorption theory. The bleeding path is decreased by the replacement of limestone powder compared with conventional concrete at same w/c. After discussed on the effect of limestone, next there are some influences of the 2 types

of concrete between self-compacting concrete and normal concrete blended with limestone powder acted on the chloride ion penetration. The different between both types are the cement content and aggregate volume fraction. The large aggregated volume fraction increases the connectivity among the interfacial pores, so that the chloride ion can easily penetrate into concrete. Moreover the total chloride concentration is in the unit of % by weight of chloride ion to cement ratio, thus the total chloride concentration in self-compacting concrete is smaller than normal concrete. In the opposite, the aggregate can be replaced the capillary and gel porosity in concrete also. The best way is to find the critical aggregate volume fraction to produce the best chloride ion resistance (see in chapter2 [15]).

In conclusion, the tests show the better resistance against chloride penetration expressed by diffusion coefficient in the case of self-compacting concrete than normal concrete. The limestone powder could be improved the resistance of chloride ion penetration when compared with normal concrete at the same condition. The reduction of chloride penetration is achieved in the case of fog test judged against the soaking test. The diffusion coefficients between top surface and bottom surface in any w/c were shown variously.

Proposal of Analysis Method

In the past, there are many analytical models to predict the behavior of chloride ion ingress for example Ref. [2,3,4]. Their concepts were explained the behavior of ion adsorption that the chloride penetration can be predicted by diffusion theory, ion adsorption by reactive and non-reactive materials [2,4] and moisture movement [3] together in a specimen. In those references, the diffusion coefficient is assumed a time-independent value for a type of mix proportion. Some other researchers investigated the chloride ion penetration by applying the concept of Fick's second law [5,6,7&10] and displayed the relationship between diffusion coefficients with time or depth dependent function. In fact, the diffusion coefficient for a specimen should be constant for all parts or higher at the surface level because of skin effect [5], but it decreased with time because of the development of microstructure and strength (the decrement of pore volume inside a specimen by hydration process). Comparison the Fick's second law with the method discussed above, the chloride ion concentration along the depth computed by Fick's second law seemed to be covered the behavior of diffusion and ion adsorption in both reactive and non-reactive materials (excepted on the surface layer) by assumed it as a non-steady condition. The limitation of Fick's second law is used for the case of a specimen in a regular environment. Many papers used basically the chloride ion concentration of solution as the boundary condition at the exposed surface and applied the Fick's second law to estimate a diffusion coefficient. In fact, the total chloride ion at outer surface is the concentration of solution, but inner surface is started at zero concentration and increased with time by diffusion and ion adsorption. Thus the chloride ion concentration in the solution cannot be applied to the boundary condition. It is necessary to find the chloride ion concentration at the time of consideration. Some researchers had already analyzed by assuming the boundary condition with the exponential function of time or square root of time [5,11]. In this paper, the concentration for the boundary condition was assumed in the logarithm function of time, because the chloride ion concentration is increased and remained a constant value at a long period of time. The experimental results were observed the total chloride ion concentration at every 5 mm and computed the diffusion coefficients. Referred to chapter 3, the specimens were contained some amount of bleeding, which was affected to the total chloride ion along the depth. In this paper, it was assumed that the diffusion coefficient along the depth is constant because of the same properties of concrete. Even though it was contained a degree of the bleeding effect, it's assumed to use an average value to define a diffusion coefficient. The diffusion coefficients for various proportions of cement replaced by limestone powder were observed by Fick's second law. By the way the first objective is to find the diffusion coefficient for this set of specimens in order to understand how the types of concrete, the types of test, the amount of cement replaced with limestone powder, time and bleeding effect affected the chloride ion penetration. The second is the amount of total chloride ion concentration at inner surface with time dependence. The procedures for both objectives were explained with particulars in chapter 4.

Literature Review

Modeling of Chloride Ion Movement in The Surface Layer of Hardened Concrete. (Maruya, T, Tantermsirikul, S, and Matsuoka, Y)

A model for surface chloride condensation was proposed by the concept of the ion adsorption. The model was explained how the surface of concrete could have higher amount of chloride ion concentration than the submerging solution. The behavior of chloride penetration cannot be explained by only diffusion theory. The authors had shown the condensation mechanism at the exposed surface by figure (1).

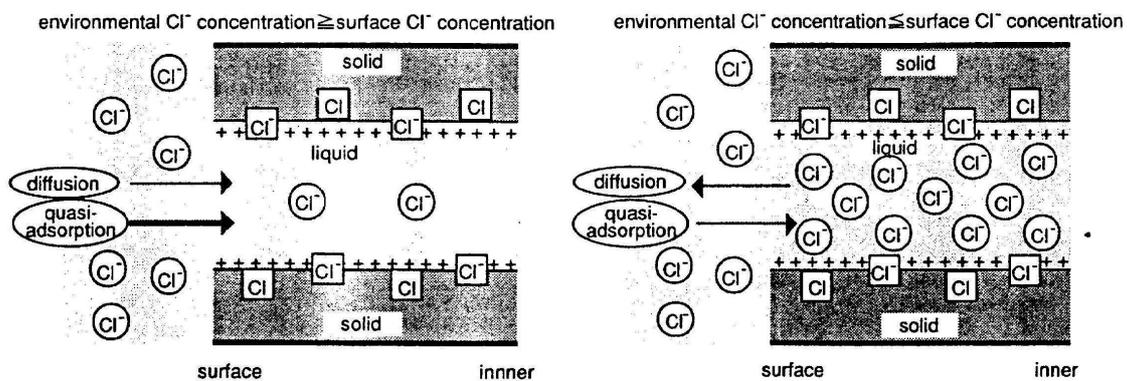


Fig1: Condensation mechanism of chloride ions in the surface layer of concrete

Considering both diffusion and condensation of chloride ion adsorption can simulate the movement of chloride ion in the submerged case, as expressed by Eq.(1).

$$F^c = F_c + S_c (C_{free}) \quad (1)$$

where F^c : total flux of chloride ion entering the concrete at surface and is the sum and the sum of the fluxes due to diffusion and ion adsorption ($\text{mol}/\text{cm}^2/\text{day}$), F_c : the flux of concrete ions due to diffusion only ($\text{mol}/\text{cm}^2/\text{day}$), and S_c : the flux of chloride ion due to ions adsorption only ($\text{mol}/\text{cm}^2/\text{day}$) and is a function of free chloride content at 1cm. from the exposed surface. The formula for S_c can be obtained by the chloride penetration results by Eq.(2).

$$S_c = (1.4 \cdot 10^{-5}) \cdot \exp(-1.15 \cdot C_{free}(1,t)) \quad (2)$$

where S_c : used for 100% cement without blended pozzolanic materials.

The Durability Standard Specification for Concrete (JSCE, 1999)

The chloride ion penetration was examined in the chapter of 'Durability Examination of Concrete Structure'. The code was purposed the steel corrosion accompanied by ingress of chloride ion, which considered by the limitation of chloride ion concentration of concrete at the location of steel alignment. The value of 1.2 kg/m³ for chloride ion concentration at steel located was purposed to be a safety for steel-corrosion generation. The rate of chloride ingress depends on the properties of concrete, which can be varied by the mix proportion. The chloride penetration by Fick' 2nd law was used to explain the total chloride along the depth from exposed surface as shown in Eq. (3).

$$C_d = C_o(1 - erf(\frac{0.1 \cdot c}{2\sqrt{D_d \cdot t}})) \quad (3)$$

Where, C_d : the design value of chloride ion concentration in reinforcement steel position.

C_o : the chloride ion concentration in concrete surface (kg/m³)

c : expected value of concrete covering (mm)

D_d : the design value of diffusion coefficient of chloride ion (cm²/year)

$$= D_k \cdot \gamma_c$$

D_k : diffusion coefficient of the chloride ion in concrete (cm²/year), assumed in the no crack structure and estimated by eq.(4) as follows:

$$\log(D) = [4.5(w/c)^2 + 0.14(w/c) - 8.47] + \log(3.15 \times 10^7) \quad (4)$$

Note: the equation is used for the case of 100% OPC as a total powder and is estimated from the actual structure with non-uniform environment.

t : durable life to ingress of chloride ion (year). In general, 100 year of durable life is the maximum of the chloride ion concentration in steel position evaluated by the formula above.

γ_c : material coefficient of concrete. In general, it is good as 1.0. However, it is better as 1.3 concerning top part of concrete generally. If there are no quality difference for all parts of structure and curing time, it is good to be use as 1.0.

erf. (s) :defined as an error function which is expressed as

$$erf(s) = \frac{2}{\pi^{1/2}} \int_0^s e^{-\eta^2} d\eta \quad (5)$$

This prediction formula is used the thing based on diffusion theory, since the diffusion is the phenomenon that the concentration difference serves as driving force. However the chloride ion in concrete is fixed and adsorbed in the cement hydrant and concrete ingredient, which should be added more than diffusion theory only.

The Investigation on Minimum Maintenance for Prestressed Concrete Bridge, (Civil Engineering Research Center, Ministry of Construction, 2000 [16])

Referred to *The Durability Standard Specification for Concrete* (JSCE, 1999), this paper was investigated on actual structure and improved the new design approach differed from previous concept. The investigation was separated the structures location into the structures along Japan Sea area, along the Pacific Ocean, and Setonaikai area. The concentrations of salt in those areas are different in concentration for a whole year. Thus the consideration of chloride ion penetration for a structure depends on the location of the structure. The concentration of salt contained in air also differs by the distance from the seashore. It is meant that the value of the chloride ion concentration at surface of a structure should be known as the boundary condition. The authors created the formula to compute the chloride ion concentration at surface of structure at any distance from seashore and also compared with the previous reference as shown in fig. 2

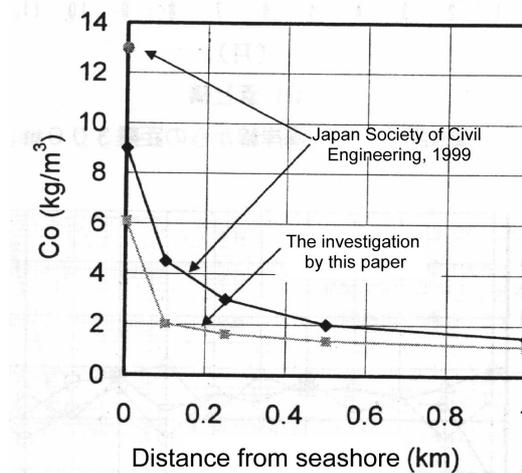


Fig. 2: The relationship between the surface concentration and distance from seashore.

From Fig. 2, the formula of C_o was proposed by equation 6 & 7 as follows:

$$C_o = 1.2 \cdot C_{air}^{0.4} \quad \text{and} \quad (6)$$

$$C_{air} = C_1 X^b, \quad b = -0.6 \text{ constant} \quad (7)$$

where:

C_o : Chloride ion concentration at surface of a structure

C_{air} : The flux of chloride ion in air ($\text{mg}/\text{dm}^2/\text{day}$, mdd)

C_1 : The unit flux of chloride ion (mdd)

X : Distance from seashore (km)

The different assumption of chloride ion concentration at surface was also developed more accurately than the previous approach to the actual value as shown in fig. 3. A long-term structure subjected to chloride ion concentration would have the concentration at inner surface higher than the outer surface, C_o . The appropriate design value for diffusion coefficient was revised again more precisely.

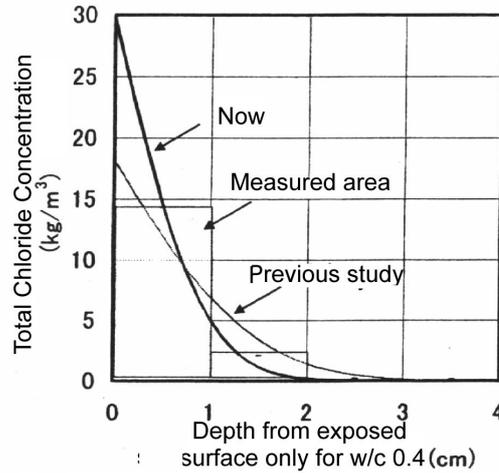


Fig. 3: The comparison of the total chloride concentration curves between previous assumption and this paper

The design diffusion coefficient was computed from the total chloride concentration curve from the actual structures, which can be said that it is absolutely different from the experimental data obtained from laboratory. The actual structures were subjected to non-uniformity of the boundary chloride ion concentration, so that the diffusion coefficient is smaller than the experimental result with the uniform boundary condition explained by fig. 4.

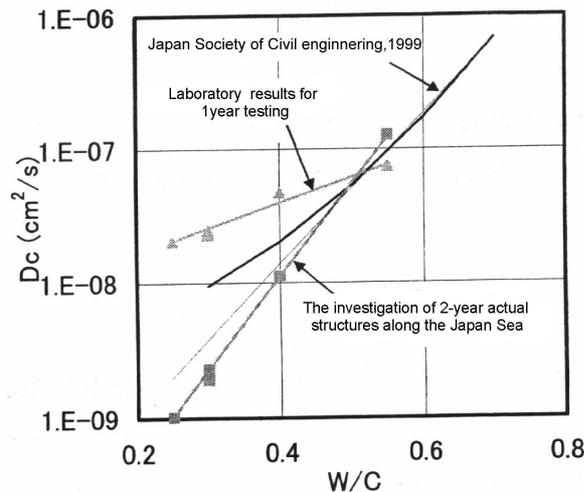


Fig. 4: The diffusion coefficient against w/c curve

This paper purposed the model to explain chloride ion movement phenomenon in concrete, which separated into 3 mechanism of free chloride, bound chloride and ion adsorption. The bound chloride and ion adsorption was modified from ref. (2), but free chloride was explained by the mass balance as shown in Eq. (8)

$$\frac{\partial}{\partial t}(\phi SC_{cl}) + \text{div}J_{cl} - Q_{cl} = 0 \quad (8)$$

where Q_{cl} : the rate of binding or the change of free chloride to bound chloride per unit volume of concrete (mol/m³/s)

J_{cl} : flux vector of the ion (mol/m²/s)

ϕ : porosity of the porous media

S : degree of saturation of the porous medium

C_{cl} : concentration of ions in the pore solution (mol/l)

For ion adsorption expressed by fig.1, the authors modified the equation from Eq. (2) to Eq. (9)

$$q_{ads} = 6.5 \times 10^{-3} \cdot \exp(-0.8 \cdot C_{cl}) \quad (9)$$

The literatures were led me well understand the chloride ion penetration in concrete. They were displayed in detail how a chloride ion concentration was differed along the depth of concrete and a various type of mix.

A Multicomponent Composite Porous Medium, ('Modeling of Concrete Performance', Maekawa K., Chaube R., Kishi T., 1999 [15])

There are three basic media, which is referred to as the components of concrete. These are: (a) the hardened cement paste matrix; (b) the aggregate cement-paste matrix interface and bleeding paths, called channel; (c) the aggregates. These three basic media are shown in the fig. 5 given below.

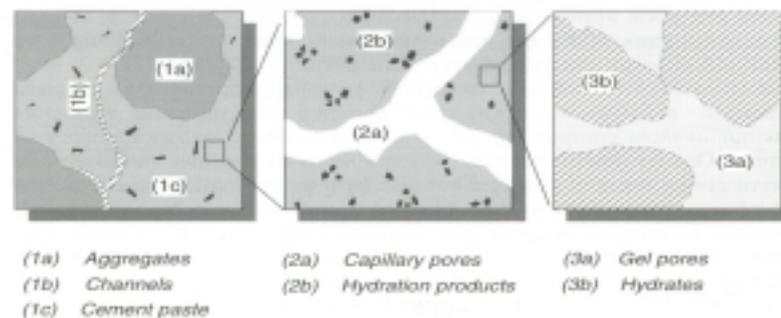


Fig.5: The multicomponents of concrete

The amount of aggregate volume fraction plays an important role in deciding the overall transport behavior. It had been reported that the porosity within the interfacial zone near aggregate surface could be up to 3 times the porosity of bulk matrix. The water to cement ratio near aggregate surfaces is usually larger than the wall effect, which means that cement powder particles near a wall-like surface cannot pack efficiently as in the bulk medium. It leads to coarse microstructure and high porosity near aggregate surface, whose thickness depends on the size of aggregate. The aggregate volume fraction also plays on the effect of bleeding path of water movement modeled by hard core soft shell theory as shown in fig. 6

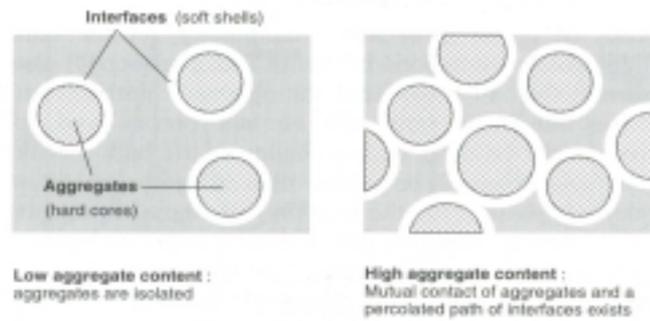


Fig. 6: Schematic representation of hard core soft shell model

The volume fraction of aggregate at which such a percolation of interface occurs can be called the *critical volume fraction* of the aggregate. When the aggregate volume fraction is increased, a larger amount of interfaces contacts occur. This leads to a larger of the interfaces becoming connected together. Then the model can be predicted the amount of interfacial volume fraction percolated related with the aggregate size and the aggregate volume fraction. The minimum value of interfacial volume fraction percolated can explain the critical aggregate volume fraction as shown in fig.7

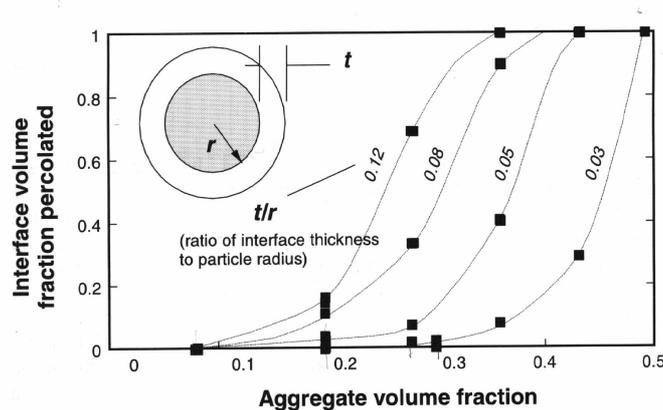


Fig. 7: Computed percolation curves of a composite containing spherical, equally sized aggregate particles

Experimental Outlines

The test was held 10 mix proportions as shown in table (1) for testing chloride movement in 2 different types of soaking and fog test. First 5 mixes are designed as self-compacting concrete blended with limestone powder at $w/c = 0.3, 0.4, 0.5, 0.6$ and 0.7 . Other 5 mixes are normal concrete blended with limestone powder at equal of w/c values as above. The coarse aggregate was used at 53% by solid volume and fine aggregate was used at 45% by mortar volume. The large size gravel and small size gravel were used as coarse aggregate in the proportion of 1: 2.333 by weight. The material properties were shown in table (2) and the test for gradation (Appendix C) and solid volume were shown in table 4. The deionized water was utilized for mixing water to prevent the effect of some reactive ions. The mixing procedure had been separated between self-compacting concrete and normal concrete. Firstly for self-compacting concrete, the order is cement+sand (30sec)→water equal to 70% by volume powder (90sec) →rest of water+SP (30sec) →coarse aggregate (60sec). By this method, it can be obtained some improvement of the concrete properties in fresh state. For self-compacting concrete, the slump flow, box test and V-shape funnel speed were measured just after mixing as the properties during the fresh state as shown in table (3). Secondly for normal concrete, the order is cement+sand (30sec)→water equal to 74% by volume powder (90sec) → →coarse aggregate (60sec) → rest of water+SP (60sec). This method is aimed to have concrete at very low w/c surrounding the aggregate particles and increment of slump value as shown in table (3). The cylindrical concrete specimens of 10 x 20 cm. were cast just after mix and leave for 24 hours under sealed condition, and then removed into the curing pond at constant temperature 20°C for 28 days. The specimens were needed to coat all surface excepted top and bottom sides with the purpose of exposing to the control environment. The aim of study is for understanding the bleeding effect by the inequality of data from both sides. The specimens after 28 days curing will be transferred to 2 testing conditions: soaking test and fog test. The important caution is that before putting a specimen into the test, it should be provided the water absorption for a while in order to fill up porosity with water and to protect the suddenly sucking of chloride solution at the surface of specimens. The condition of soaking test is 20°C and chloride ion concentration of 5% ($\text{NaCl} = 8.24\%$)[9]. The fogging test is supposed to be similar to the offshore neighborhood with the average temperature of 25°C . The fog test was used the same concentration of chloride ion concentration with the rate of $0.6 \text{ m}^3/\text{sec}$. The test results were procured at time of 1 month, 3 months and 5 months. The specimens were removed from the test at testing time and wait until it had been dried before cutting. The specimens were cut in every 5 mm from opened surface, and crushed to be very fine. The titration machine using AgNO_3 as titration solution were used to tritrate the total chloride content from a sample. The testing procedure was referred to ASTM C114, 1997[8].

Table 1. Mix proportion for chloride testing.

NO.	Type	w/p	w/c	% replacement	cement (kg/m ³)	Ls (kg/m ³)	water (kg/m ³)	sand (kg/m ³)	gravel (kg/m ³)	SP (kg/m ³)
1	Normal	0.94	0.3	0.5	485	2	146	768	1039	4.877
2	Normal	0.94	0.4	22.6	364	106	146	768	1039	4.703
3	Normal	0.94	0.5	36.7	291	169	146	768	1039	4.599
4	Normal	0.94	0.6	46.4	243	210	146	768	1039	4.530
5	Normal	0.94	0.7	53.6	208	240	146	768	1039	4.480
6	SCC	0.94	0.3	0.5	597	3	179	774	848	9.295
7	SCC	0.94	0.4	22.6	448	131	179	774	848	6.940
8	SCC	0.94	0.5	36.7	358	207	179	774	848	5.938
9	SCC	0.94	0.6	46.4	298	259	179	774	848	5.570
10	SCC	0.94	0.7	53.6	256	295	179	774	848	4.958

Table 2. Material Properties

Material type	Specific gravity	% Absorption	Surface area (cm ² /g)
Cement	3.15	-	3280
Ls	2.7	-	4000
Sea Sand	2.57	2.62	-
Crushed sand	2.55	2.67	-
Big gravel	2.68	-	-
Small gravel	2.66	-	-

Table 3. Properties of each mix proportion

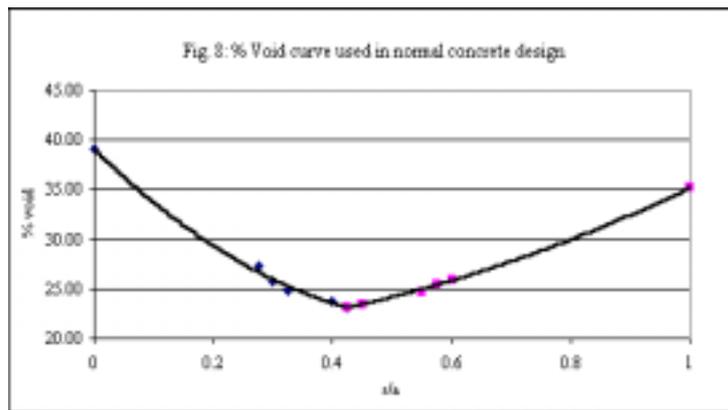
NO.	Type	w/p	w/c	Slump flow (mm. X mm.)	Funnel speed (sec.)	Box test (cm.)	Temp. (celcius)	Slump height (cm.)	Strength 28-d (MPa)
1	Normal	0.94	0.3	-	-	-	23.7	12.6	85.6
2	Normal	0.94	0.4	-	-	-	24	16.7	73.4
3	Normal	0.94	0.5	-	-	-	24.2	19	60.6
4	Normal	0.94	0.6	-	-	-	23.6	20.3	49.8
5	Normal	0.94	0.7	-	-	-	23.5	21.9	39.6
6	SCC	0.94	0.3	650*640	11.47	32.2	22.8	-	83.9
7	SCC	0.94	0.4	645*663	13.6	31.5	23.6	-	70.6
8	SCC	0.94	0.5	680*680	19.14	33	23.1	-	62.1
9	SCC	0.94	0.6	685*665	14.34	32.4	22.3	-	52.6
10	SCC	0.94	0.7	669*668	14	31.5	22.7	-	42.7

Table 4 Void Curve

Crushed sand: Sea sand = 1.02:1 by volume (1:1 by weight)

Large-size gravel: Small-size gravel = 1:2.333 by weight

	35.14	s/a	% void
% void of sand =	42.18	0	39.06
% void of gravel =		0.275	27.26
		0.3	25.67
		0.325	24.88
		0.4	23.68
		0.425	23.12
		0.45	23.41
		0.55	24.63
		0.575	25.44
		0.6	25.96
		1	35.14



Experimental Results & Verification

The specimens were mixed with the replacement of limestone powder blended with cement, which was designed by varying the weight ratio of water to cement from 0.3-0.7 at the constant volume ratio of water to powder at 0.94 and constant aggregate volume fraction. The total chloride ion concentrations along the depth of a specimen from both soaking and fog test were examined with the time of 1, 3 and 5 months in order to estimate the specimens' diffusion coefficient. The diffusion coefficient was explained in Part 1, and the surface chloride ion concentration was discussed in Part 2. The overall steps of calculation for the experimental data were expressed as follows:

1. Computed the average total chloride ion concentrations in every 5 mm depth in the unit of % by weight of cement.
2. Set the total chloride ion concentration at 0-5 mm as a boundary condition, because the real boundary condition at inner surface was still unknown.
3. Computed an average value of the diffusion coefficients obtained from latter depth using equations (3 & 5) for 3 different periods of test.
4. After got an average value of diffusion coefficient, used the equation 3 to compute the inner surface (C_o) by assumed $C_d =$ the total chloride ion concentration at 0-5mm, c is 2.5 mm and $D_d =$ computed diffusion coefficient from step 3.
5. Created the empirical formula for the total chloride ion concentration at inner surface as expressed in equation 13.

Part1: Total chloride ion concentration and diffusion coefficient

On the figure 9-38, the experimental results (see in Appendix A.) were shown the total chloride ion concentration varied by type of test, penetrated depth, w/c and time in the unit of % by weight of cement. The total chloride ion concentration curves were shown with included top and bottom surface and 2 types of concrete curves in a graph. These results are shown the high concentration at the surface and the decrement of total chloride ion concentration along the depth inside concrete. The higher diffusion coefficient, the higher total chloride ion concentration is basically observed. The total chloride between top and bottom surface of each type of mix are shown differently. The reason is that the rich of paste volume were contained on the top part but the rich of aggregate were contained on the bottom part. After casting concrete, the specimens were affected by bleeding in theirs, then the water was moved up and aggregates were sunk to the bottom part. Thus concrete was not uniformed and a new formation along the depth was taken place. The top part became increasing of paste volume and also w/c in paste matrix, but decreasing of aggregate's volume. In the other part, the getting higher of aggregate's volume covered with low w/c paste matrix was observed. When the chloride ion was penetrated it was stored in the pores of concrete specimen, thus the amount of total chloride in a specimen was related to the pore volume and the connection of pore paths. The aggregate effect is on the reduction of capillary pores and gel pores by replacing of paste volume, but the induction of the interfacial pores and

path connection was become apparent. The unit of total chloride was used by the percentage of weight of cement per 1m^3 of volume, thus the computed total chloride ion concentration was overestimated on the top part and underestimated on the bottom part. Therefore the difference was turned out to be decreasing at inside depth. In conclusion, it was revealed that the top part of a specimen had a chloride penetration curve higher than that of the bottom part and those curves became narrow through the depth.

The observation was conducted to the difference between self-compacting concrete and normal concrete with the same water to cement ratio. On the figures, chloride penetration paths of self-compacting concrete were under those of normal concrete. They could be concluded that the durability on chloride penetration in case of self-compacting concrete was higher than normal concrete in any water to cement ratio even though the 28-day compressive strengths of self-compacting concrete were lower than normal concrete in some mix proportions. By the figures, they can be explained in addition that the longer time of test, the larger deviation of total chloride ion concentration curve between 2 types was investigated. The reason is that self-compacting concrete was used aggregate volume fraction less than in case of normal concrete, so among the pores in the interfacial zone were not connected continuously, and then the chloride ions were slowly penetrated through a specimen (see in Chapter2). Moreover the inconsistency of total chloride ion concentration at a depth from exposed surface between top and bottom part of self-compacting concrete was narrower than those of normal concrete caused by bleeding effect. Thus, It was found that the bleeding in case of self-compacting concrete is lower than in case of normal concrete due to the needless of a vibration force and the viscosity of the paste to prevent the elevation of water is also higher. It is the advantage to use self-compacting concrete for an actual structure not only no vibration is required, but also durability concerned.

From the total chloride ion concentration curves, the depth at 2.5 mm was set to be the initial condition to compute the diffusion coefficient in order to avoid some effects that were discussed in Part 2. The equations of Fick's second law and error function shown in chapter 2 [1] were applied to calculate the average diffusion coefficients for each w/c. A specimen is contained some amount of bleeding which is caused by w/c, water content, % replacement of limestone powder and vibration energy. Thus, the new alignment of aggregate and also real w/c along the depth is unclear. After bleeding was happened, the top part of the specimen was contained less of aggregate content but higher in w/c, and then the diffusion coefficient would be differed between top and bottom. Therefore it is still unclear about it, so the average value for diffusion coefficient along the depth of a specimen was assumed to present at this time (see Appendix B). Moreover the verification of diffusion coefficients with conventional concrete from the references (see in Appendix E) was done in fig (39-42). After all, the diffusion coefficient for a mix was used in the analysis of the chloride ion concentration at surface of the same concrete specimen (see in Part 2).

Fig. 9: Total Chloride for concrete with w/c 0.3 at 1month in soaking test.

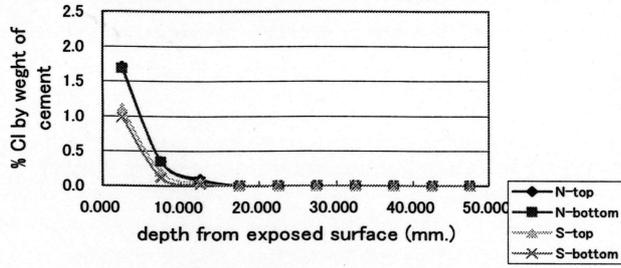


Fig. 10: Total Chloride for concrete with w/c 0.3 at 1month in fog test.

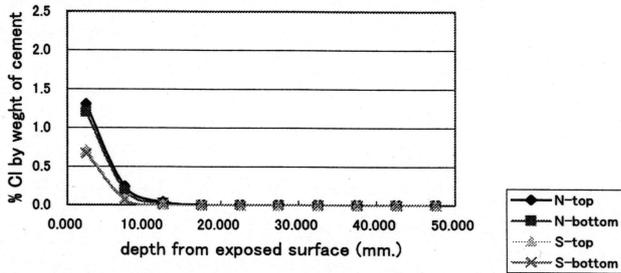


Fig. 11: Total Chloride for concrete with w/c 0.4 at 1month in soaking test.

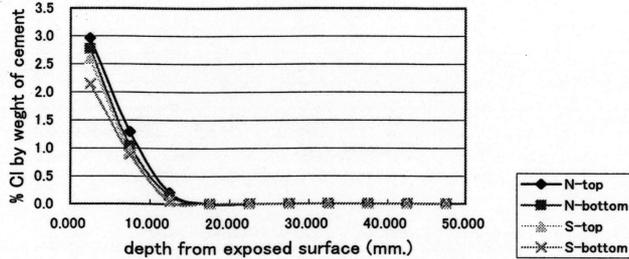


Fig. 12: Total Chloride for concrete with w/c 0.4 at 1month in fog test.

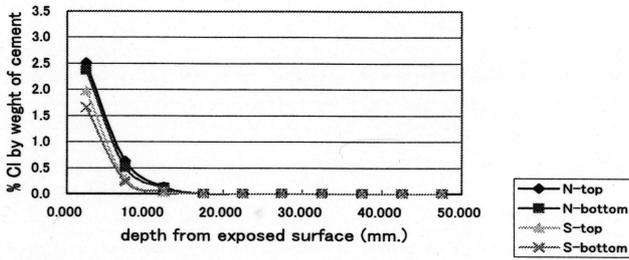


Fig. 13: Total Chloride for concrete with w/c 0.5 at 1month in soaking test.

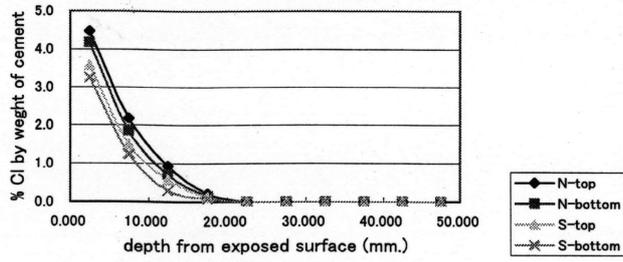


Fig. 14: Total Chloride for concrete with w/c 0.5 at 1month in fog test.

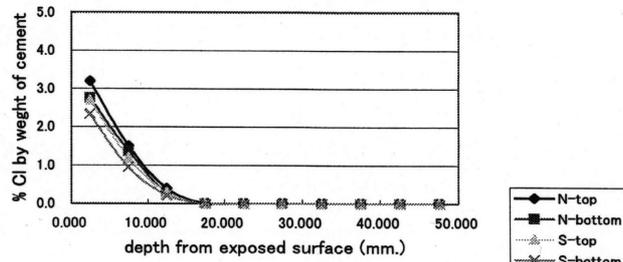


Fig. 15: Total Chloride for concrete with w/c 0.6 at 1month in soaking test.

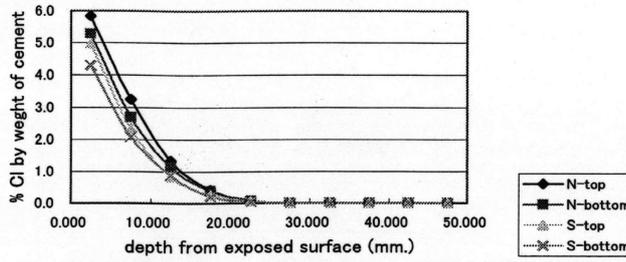


Fig. 16: Total Chloride for concrete with w/c 0.6 at 1month in fog test.

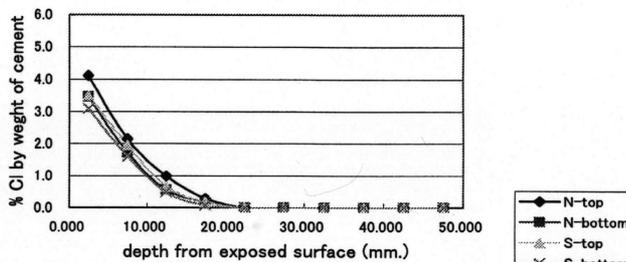


Fig. 17: Total Chloride for concrete with w/c 0.7 at 1 month in soaking test.

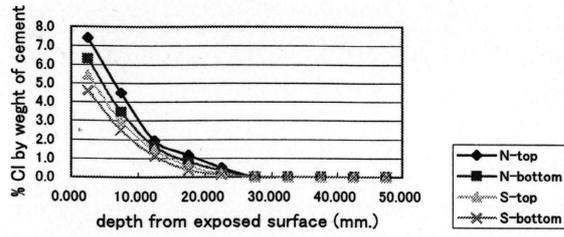


Fig. 18: Total Chloride for concrete with w/c 0.7 at 1 month in fog test.

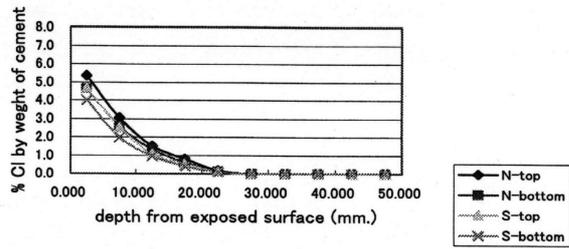


Fig. 19: Total Chloride for concrete with w/c 0.3 at 3-month in soaking test.

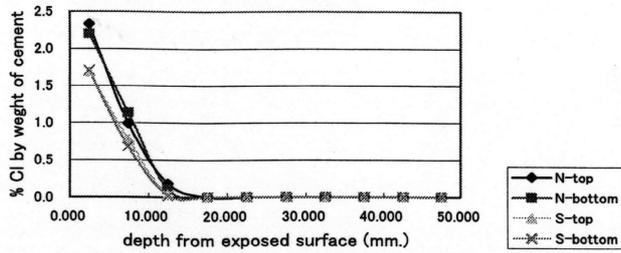


Fig. 20: Total Chloride for concrete with w/c 0.3 at 3-month in fog test.

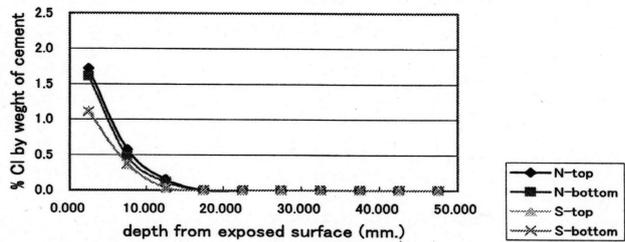


Fig. 21: Total Chloride for concrete with w/c 0.4 at 3-month in soaking test.

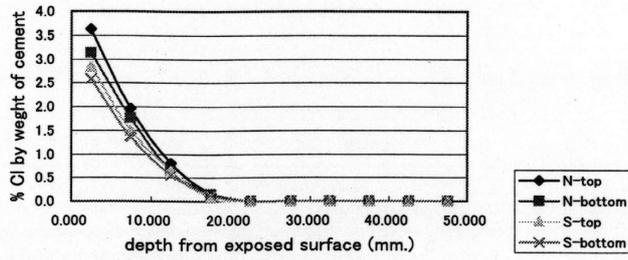


Fig. 22: Total Chloride for concrete with w/c 0.4 at 3-month in fog test.

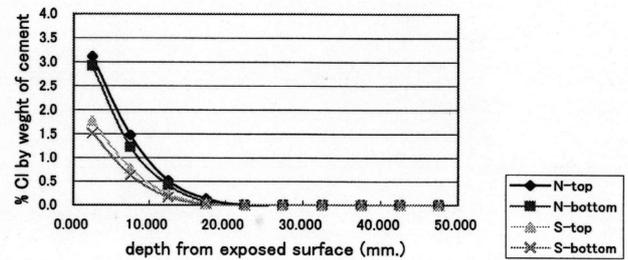


Fig. 23: Total Chloride for concrete with w/c 0.5 at 3-month in soaking test.

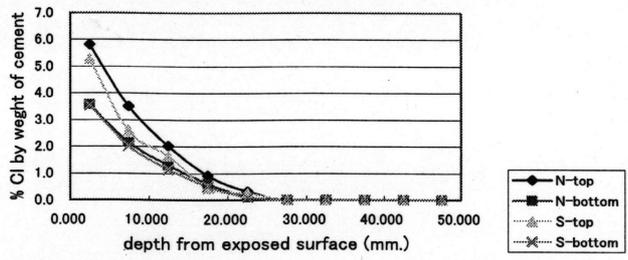


Fig. 24: Total Chloride for concrete with w/c 0.5 at 3-month in fog test.

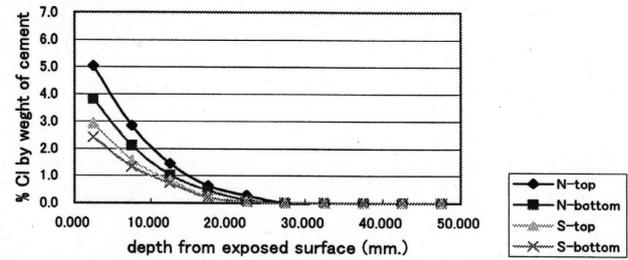


Fig. 25: Total Chloride for concrete with w/c 0.6 at 3-month in soaking test.

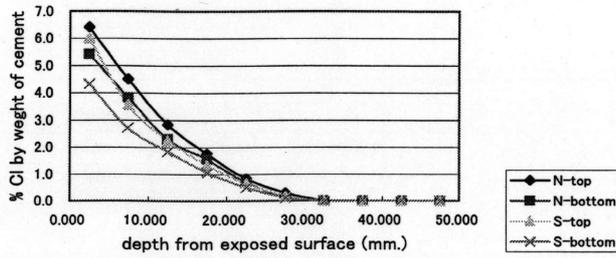


Fig. 26: Total Chloride for concrete with w/c 0.6 at 3-month in fog test.

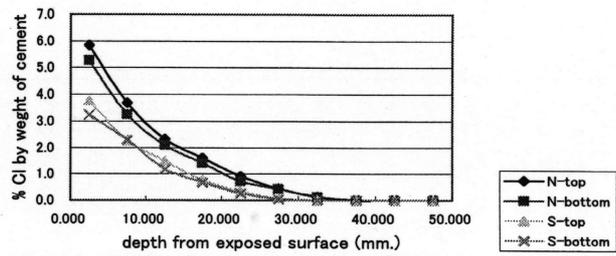


Fig. 27: Total Chloride for concrete with w/c 0.7 at 3-month in soaking test.

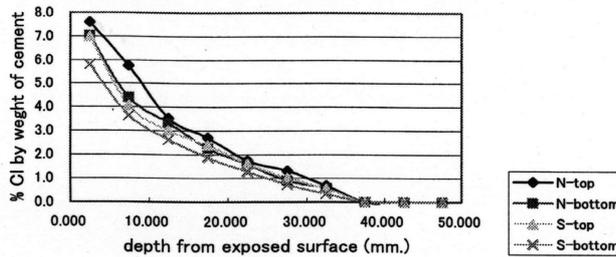


Fig. 28: Total Chloride for concrete with w/c 0.7 at 3-month in fog test.

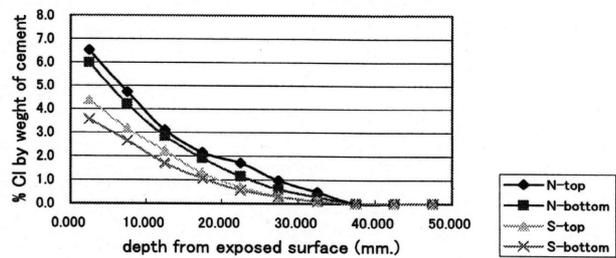


Fig. 29: Total Chloride for concrete with w/c 0.3 at 5-month in soaking test.

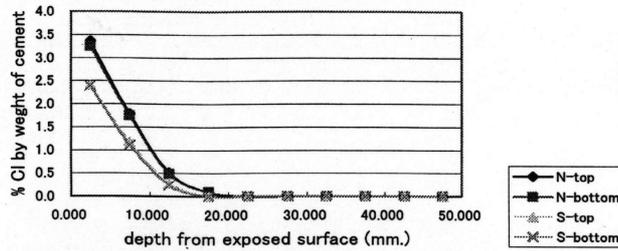


Fig. 30: Total Chloride for concrete with w/c 0.3 at 5-month in fog test.

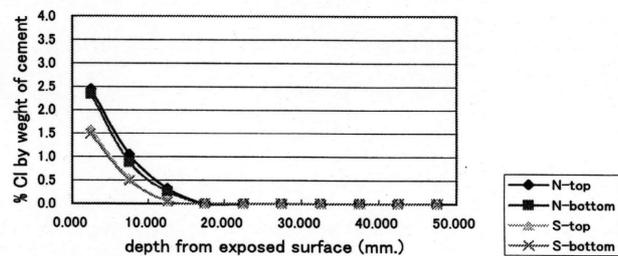


Fig. 31: Total Chloride for concrete with w/c 0.4 at 5-month in soaking test.

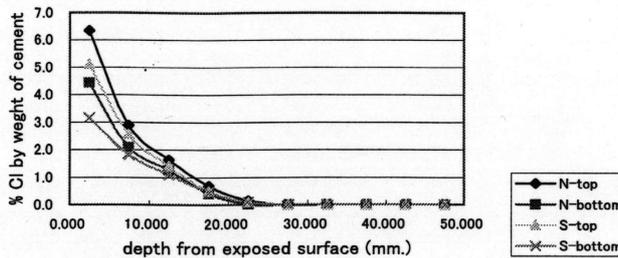


Fig. 32: Total Chloride for concrete with w/c 0.4 at 5-month in fog test.

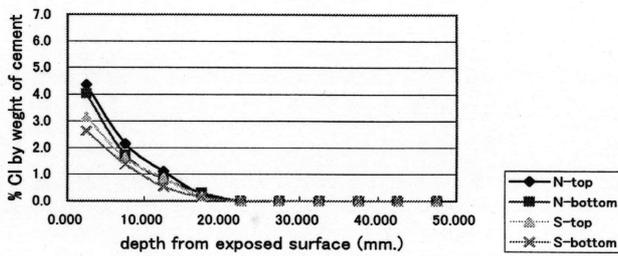


Fig. 33: Total Chloride for concrete with w/c 0.5 at 5-month in soaking test.

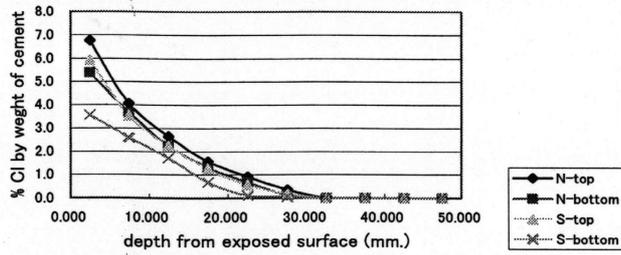


Fig. 34: Total Chloride for concrete with w/c 0.5 at 5-month in fog test.

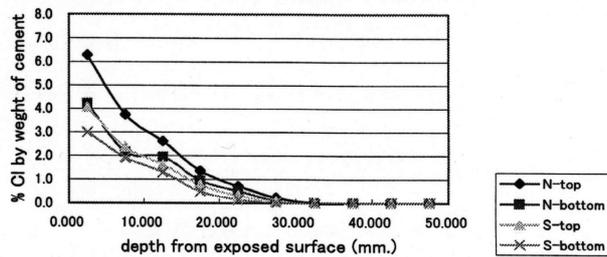


Fig. 35: Total Chloride for concrete with w/c 0.6 at 5-month in soaking test.

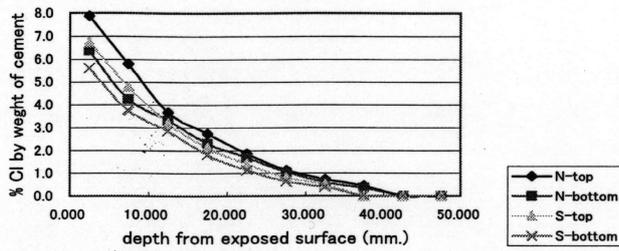


Fig. 36: Total Chloride for concrete with w/c 0.6 at 5-month in fog test.

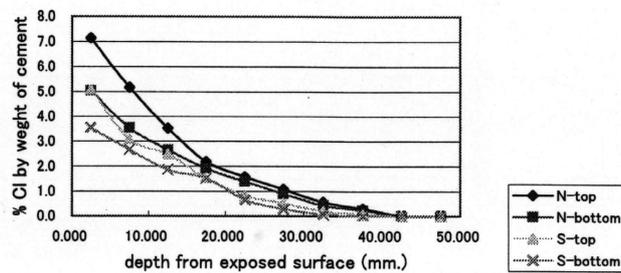


Fig. 37: Total Chloride for concrete with w/c 0.7 at 5-month in soaking test.

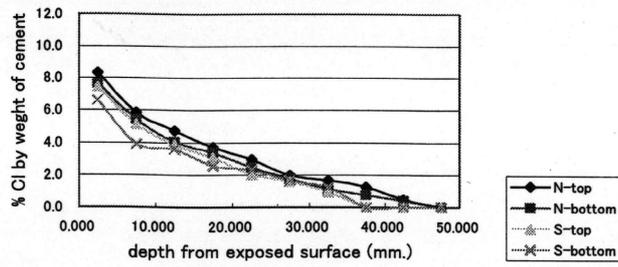
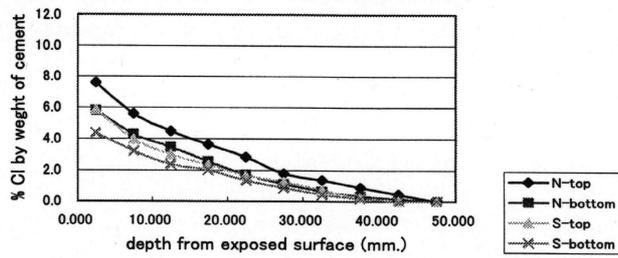
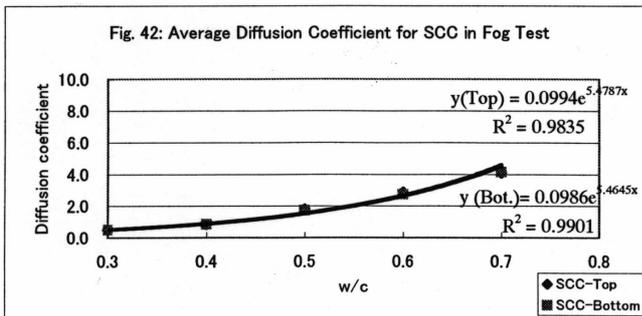
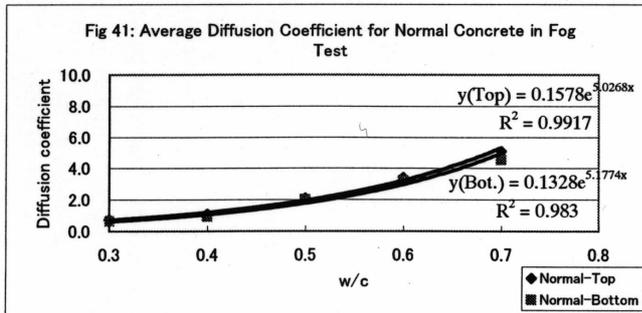
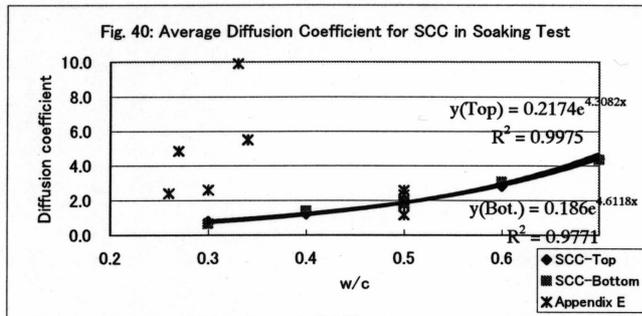
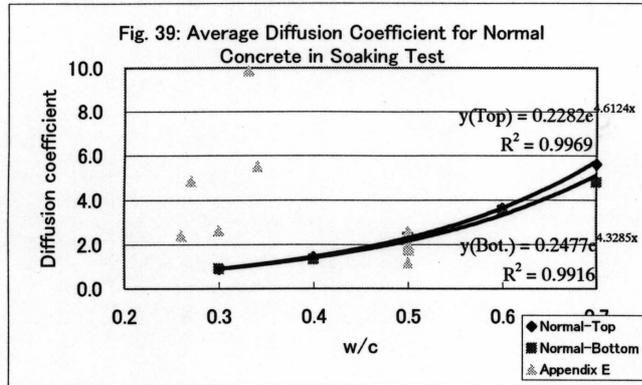


Fig. 38: Total Chloride for concrete with w/c 0.7 at 5-month in fog test.



Verification of experimental data with conventional concrete from App. E



Part 2: The analysis of chloride ion concentration at inside surface of concrete.

As discussed, many researchers assumed the condition of chloride ion concentration in the submerged solution as follows:

$$t = 0 \ \& \ x = 0 \quad \rightarrow \quad C_{o(0,0)} = C_{\text{solution}}$$

and

$$C_{o(x,t)} = C_{\text{solution}} \times f(t) \tag{10}$$

or

$$C_{o(x,t)} = C_{\text{solution}} + C_{\text{ion adsorption}} \tag{11}$$

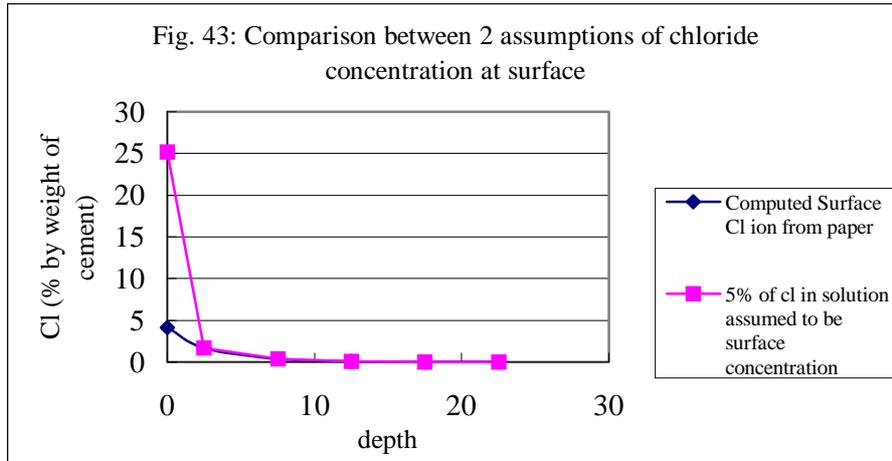
where $C_{\text{ion adsorption}}$ is the ion adsorption of chloride ion concentration at surface layer [2,3]

Table 5: Shows a Mean Constant Diffusion Coefficients from Appendix B

Soaking Test					Fog Test				
w/c	Top Surface		Bottom Surface		w/c	Top Surface		Bottom Surface	
	Normal	SCC	Normal	SCC		Normal	SCC	Normal	SCC
0.3	0.886	0.784	0.897	0.648	0.3	0.735	0.490	0.631	0.490
0.4	1.432	1.194	1.328	1.375	0.4	1.063	0.836	0.933	0.831
0.5	2.459	1.990	2.316	1.905	0.5	2.081	1.796	2.019	1.722
0.6	3.607	2.821	3.528	3.064	0.6	3.402	2.875	3.193	2.738
0.7	5.602	4.395	4.794	4.352	0.7	5.076	4.085	4.541	4.152

From the data table in Appendix D, the chloride ion in solution is constant at 5% of water, and was converted into % by weight of cement in each mix proportion. The test was observed that the total chloride content at the inside surface was started at zero and increase with time. Then the total chloride at surface was higher than the concentration of solution at a certain time, because of diffusion and ion adsorption theory. Thus it seems to be concluded that the assumption of chloride ion in solution as the boundary condition was not exacted. For example, the total chloride ion concentration of w/c = 0.3 at top part of 28-day test data is 4.17 % for soaking test compared with 25.18 % of the solution. If the 25.18 % were used as boundary condition in order to compute a diffusion coefficient by Fick's second law, the computed diffusion coefficient would be shown a diffusion coefficient at surface lower than inside concrete. It was cleared to explain the example by fig.43 that shows large difference at surface layer, and this thing was also recommended by the literature, fig. 4.

In fact, the diffusion coefficient is one of the material properties, which should be constant along the depth proved by this figure. Some researchers used both 1. The chloride ion concentration of solution is the boundary condition and 2. The equation for diffusion coefficient was referred to Fick's second law; then at surface 0-5mm the coefficient is low. When the coefficient at 5-10mm was computed, the apparent coefficient was a mean between 2 different values from 0-5mm and 5-10mm. Thus the computed diffusion coefficient from Fick's second law was shown in the function of depth. On the other hand, in case of high w/c and long time, the coefficient could be shown inversely compared with the example.



It can be said that the outer surface contained 5% of chloride ion concentration as the salt solution was not equaled the inner surface of concrete at any time. This paper was aimed to create the formula of chloride ion concentration at inner surface with the function of time, chloride ion concentration of the solution, cement content, relative humidity and diffusion coefficient as follows:

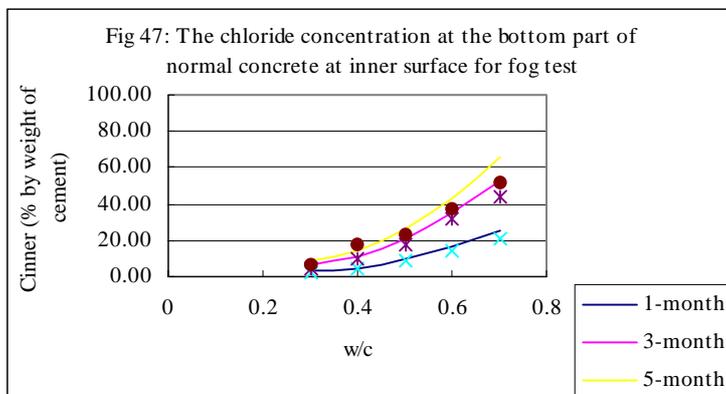
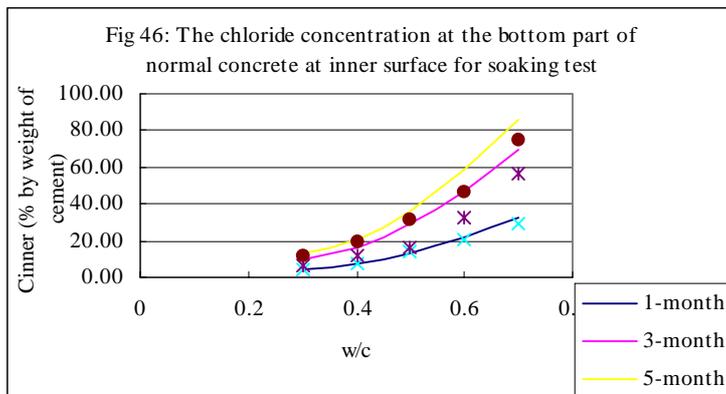
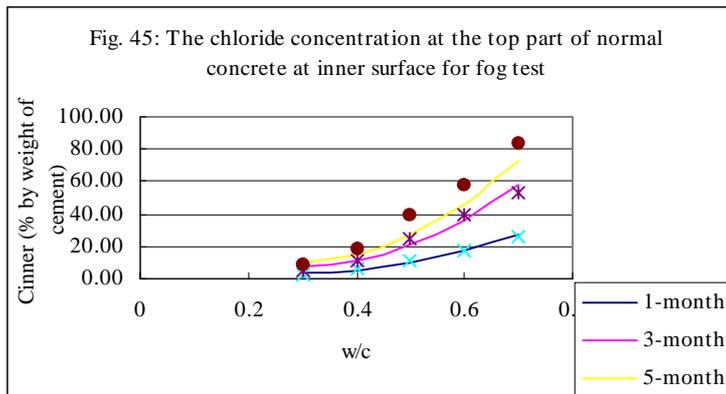
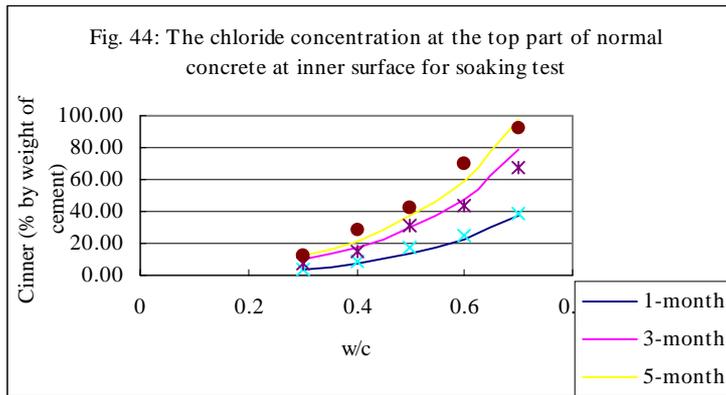
$$C_{\text{inner}} = C_{\text{outer}} \cdot \frac{\text{Unit weight}}{W_{\text{cement}}} \cdot f(t, D, RH) \quad (12)$$

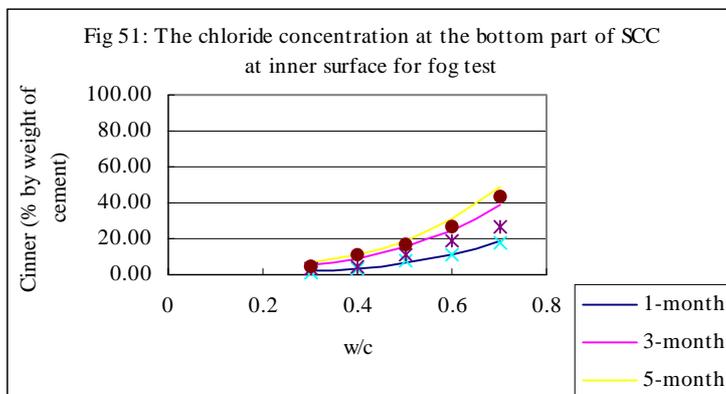
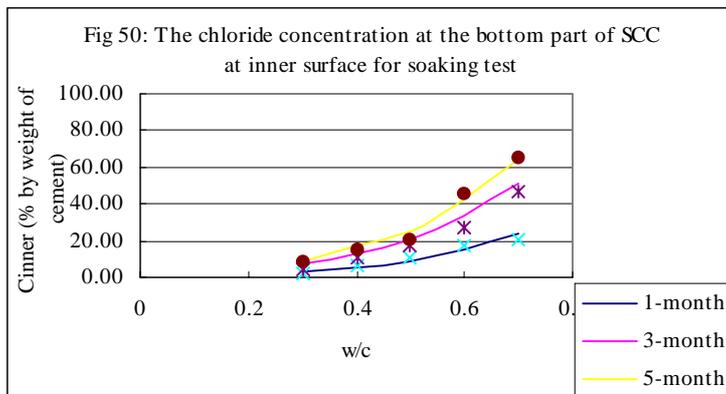
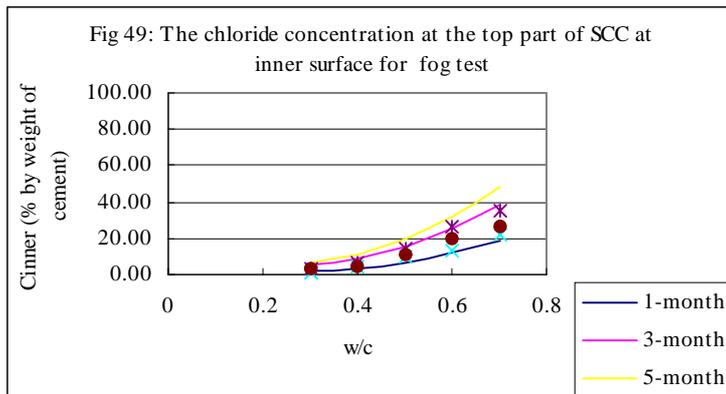
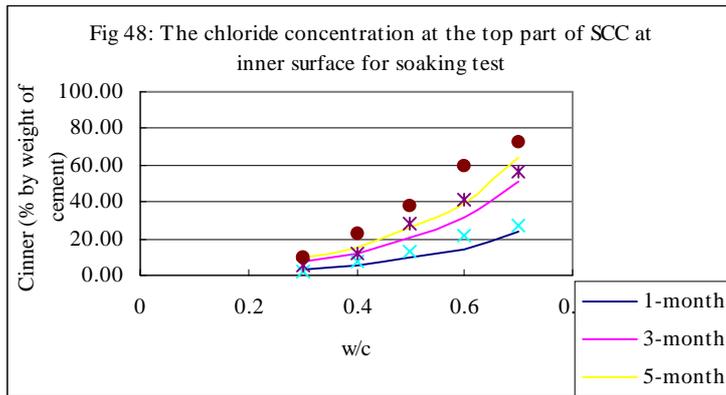
- Where C_{outer} : Chloride ion concentration in the submerge solution (% in water)
 W_{cement} : Weight of cement content (kg/m^3)
 C_{inner} : Chloride ion concentration at inner surface of concrete (% by W_{cement})
 t : Required structure's life (year)
 D : Diffusion coefficient (cm^2/year)
 RH : Relative humidity of testing environment, (for soaking test, $RH = 1$ and for fog test $RH = \approx 0.8$)

The regression method was used to identify the equation for $f(t, D)$, which is functioned as follows,

$$f(t, D, RH) = \{ \{ [(0.0930 \cdot D) + 0.1287] \cdot \text{LN}(t) \} + (0.3330 \cdot D) + 0.4002 \} \cdot RH \quad (13)$$

The curves for chloride ion concentration at inner surface and empirical formula were shown in the fig. (44-51). Finally, the design mix proportions for a structure was assumed the service life (t), mix proportion (w/c) and location of structure (C_{outer}), and then C_{inner} can be obtained. Then Fick's second law can also compute the total chloride ion concentration along the depth of covering. After all, the limitation of chloride ion concentration at the position of steel ($= 1.2 \text{ kg}/\text{m}^3$ recommended by ref. [1]) can be checked easily.





Conclusion

1. The limestone blended with cement can reduce the diffusion coefficient for chloride ion penetration at same w/c as conventional concrete.
2. The diffusion coefficient for self-compacting concrete showed the value lower than that of normal concrete therefore self-compacting concrete clarified better durable concrete in chloride resistance.
3. The outer solution cannot be applied as the boundary condition in the determination of chloride ion penetration by Fick's second law.
4. The effect of bleeding affects the difference in chloride ion penetration between top part and bottom part caused by many parameters such as w/c, water content, % replacement of limestone powder, paste volume, SP and vibration, etc.
5. The fog test provided less the diffusion coefficient than the soaking test because the relative humidity inside pore was not fulfilled with water or solution.
6. By this test, the bleeding effect is in according with chloride ion concentration, which is the same as in the case of a beam or a girder structure. Thus the test will be suitable to be used in design of a specific type of structure only. In the case of column, the bleeding effect is perpendicular to the chloride penetration route, the test of specimen that same as column will lead us to understand the effect of bleeding along the depth or a new alignment between paste and aggregate after bleeding took place.

Further Study

1. The test should be prolonged into concrete made from cement replaced with fly ash and slag.
2. The test specimen should be changed into a prism, which contains some of bleeding effect by controlling vibration energy.
3. The model for understanding of a new formation of paste property and segregation of aggregate.
4. The criteria to match the experimental result with the actual application or design purpose.

References

1. Japan Society of Civil Engineers, *Standard specification for durability of concrete, 1999* (in Japanese)
2. Maruya T., Tangtermsirikul S. and Matsuoka Y., *Modeling of Chloride Ion Movement in The Surface Layer of Hardened Concrete*, Concrete library of JSCE, No. 32, December 1998, pp. 69-84
3. Ishida T., *An Integrated Computational System of Mass/Energy Generation, Transport and Mechanics of Materials and Structures*, The doctoral thesis submitted to University of Tokyo, March 1999, pp 36-41
4. Plang-ngern S. *Chloride Binding Capacity in Fly Ash Concrete*, The master thesis submitted to International Institute of Technology Thammasat University, 1999
5. Carmen A., Jose M. D., and Cruz A., *Mathematical Modeling of a Concrete Surface "Skin Effect" on Diffusion in Chloride Contaminated Media*, Elsevier Science Ltd., 1997
6. Yamamoto A., Motohashi K., Misra S., and Tsutsumi T., *Proposed Durability Design for RC Marine Structures, Concrete Under Severe Conditions: Environment and Loading* (volume one), published by E&FN Spon, 1995
7. Gjorv O.E., Sakai K., *Testing of Chloride Diffusion For Concrete, Concrete Under Severe Conditions: Environment and Loading* (volume one), published by E&FN Spon.,1995
8. ASTM C 114-97a, *Standard Test Methods for Chemical Analysis of Hydraulic Cement*, 1997, pp 111-112
9. Maruya T., Matsuoka Y., and Tangtermsirikul S., *Simulation of Chloride Movement in Hardened Concrete*, Concrete Library of JSCE, No.20, 1992, pp.57-70
10. Chatterji S., *On The Applicability of Fick's second law to Chloride Ion Migration Through Portland Cement Concrete*, Cement and concrete research, Vol. 25, No. 2, 1995, pp.299-303
11. Weyers E. R., *Service Life Model for Concrete Structures in Chloride Laden Environment*, ACI Materials Journal, Vol. 95, No.4, 1
12. Tang L., Andalen A., Johansson J. -O., Hjelm S., *Chloride Diffusion Coefficient of Self-compacting Concrete*, Self-compacting concrete, Edited by Skarendahl and Peterson, Rilem Proceedings Pro7, Sep. 13-14, 1999
13. Chan Y.N. S., Ji X., *Comparative Study of The Initial Surface Absorption and Chloride Diffusion of High Performance Zeolite, Silica fume and Pfa Concretes*, Cement and Concrete Composites, Vol. 21, 1999, pp. 293-300
14. Leng F.,Feng N.,Lu X., *An Experimental Study on The Properties of Resistance to Diffusion of Chloride Ions of Fly ASH and Blast Furnace Slag Concrete*, Cement and concrete research 30,No. 989-992, 2000
15. Maekawa K., Chaube R. and Kishi T., *Modeling of Concrete Performance*, by E & FN Spon, 1st Edition, 1999, pp. 107-117
16. The Civil Engineering Research Center, Ministry of Construction, *The Investigation for Minimum Maintenance for Prestressed Concrete Bridge*, December 2000, (in Japanese)

17. Sandberge P., *Studies of Chloride Binding in Concrete exposed in a marine Environment*, Cement and Concrete Research, Vol. 29, 1999, pp. 473-477

Appendix A: Tables show the total chloride ion concentration of the specimens by varying type of concrete, time, w/c and type of testing

Table A1: Shows The Total Chloride Concentration at 1 Month in Soaking Test.

W/C	Depth (mm)	(NORMAL) CONCRETE Cl/ Wcement (%)		(SCC) CONCRETE Cl/ Wcement (%)	
		Top	Bottom	Top	Bottom
0.300	2.500	1.706	1.681	1.108	0.980
	7.500	0.352	0.348	0.196	0.118
	12.500	0.094	0.063	0.046	0.023
	17.500	0.000	0.000	0.000	0.000
	22.500	0.000	0.000	0.000	0.000
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.400	2.500	2.960	2.766	2.585	2.148
	7.500	1.290	1.037	0.946	0.889
	12.500	0.203	0.147	0.056	0.048
	17.500	0.000	0.000	0.000	0.000
	22.500	0.000	0.000	0.000	0.000
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.500	2.500	4.465	4.170	3.577	3.253
	7.500	2.176	1.846	1.483	1.242
	12.500	0.929	0.716	0.576	0.288
	17.500	0.207	0.149	0.113	0.076
	22.500	0.000	0.000	0.000	0.000
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.600	2.500	5.827	5.281	4.969	4.299
	7.500	3.240	2.689	2.321	2.075
	12.500	1.329	1.117	0.834	0.879
	17.500	0.420	0.388	0.268	0.202
	22.500	0.085	0.079	0.063	0.048
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.700	2.500	7.406	6.307	5.417	4.588
	7.500	4.485	3.456	2.934	2.496
	12.500	1.952	1.622	1.435	1.103
	17.500	1.155	0.815	0.587	0.357
	22.500	0.482	0.331	0.158	0.117
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000

Table A2: Shows The Total Chloride Concentration at 1 Months in Fog Test.

W/C	Depth (mm)	(NORMAL) CONCRETE Cl/ Wcement (%)		(SCC) CONCRETE Cl/ Wcement (%)	
		Top	Bottom	Top	Bottom
0.300	2.500	1.306	1.203	0.715	0.672
	7.500	0.238	0.192	0.075	0.071
	12.500	0.043	0.022	0.005	0.004
	17.500	0.000	0.000	0.000	0.000
	22.500	0.000	0.000	0.000	0.000
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.400	2.500	2.503	2.369	1.980	1.658
	7.500	0.623	0.503	0.284	0.232
	12.500	0.128	0.108	0.032	0.047
	17.500	0.000	0.000	0.000	0.000
	22.500	0.000	0.000	0.000	0.000
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.500	2.500	3.193	2.753	2.696	2.317
	7.500	1.497	1.359	1.191	0.936
	12.500	0.388	0.284	0.292	0.223
	17.500	0.000	0.000	0.000	0.000
	22.500	0.000	0.000	0.000	0.000
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.600	2.500	4.101	3.453	3.490	3.088
	7.500	2.137	1.711	1.946	1.613
	12.500	0.995	0.565	0.653	0.476
	17.500	0.288	0.174	0.175	0.064
	22.500	0.000	0.000	0.000	0.000
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.700	2.500	5.331	4.632	4.684	4.008
	7.500	3.047	2.570	2.523	1.968
	12.500	1.515	1.312	1.081	0.941
	17.500	0.811	0.618	0.522	0.396
	22.500	0.157	0.114	0.118	0.100
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000

Table A3 : Shows The Total Chloride Concentration at 3-month in Soaking Test.

W/C	Depth (mm)	(NORMAL) CONCRETE Cl/ Wcement (%)		(SCC) CONCRETE Cl/ Wcement (%)	
		Top	Bottom	Top	Bottom
0.300	2.500	2.330	2.196	1.688	1.701
	7.500	0.987	1.135	0.774	0.675
	12.500	0.182	0.104	0.030	0.025
	17.500	0.000	0.000	0.000	0.000
	22.500	0.000	0.000	0.000	0.000
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.400	2.500	3.627	3.132	2.850	2.585
	7.500	1.966	1.769	1.507	1.367
	12.500	0.812	0.642	0.652	0.555
	17.500	0.157	0.156	0.064	0.123
	22.500	0.000	0.000	0.000	0.000
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.500	2.500	5.817	3.557	5.276	3.531
	7.500	3.499	2.150	2.572	2.025
	12.500	2.023	1.307	1.642	1.144
	17.500	0.907	0.609	0.424	0.510
	22.500	0.309	0.109	0.263	0.093
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.600	2.500	6.421	5.429	6.007	4.327
	7.500	4.507	3.830	3.566	2.694
	12.500	2.833	2.296	2.245	1.840
	17.500	1.762	1.548	1.332	1.064
	22.500	0.836	0.686	0.644	0.508
	27.500	0.298	0.145	0.187	0.116
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.700	2.500	7.591	7.030	6.995	5.803
	7.500	5.752	4.385	4.057	3.628
	12.500	3.523	3.325	2.999	2.625
	17.500	2.693	2.252	2.381	1.853
	22.500	1.729	1.578	1.605	1.257
	27.500	1.298	0.885	1.006	0.726
	32.500	0.687	0.569	0.563	0.342
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000

Table A4: Shows The Total Chloride Concentration at 3-month in Fog Test.

W/C	Depth (mm)	(NORMAL) CONCRETE Cl/ Wcement (%)		(SCC) CONCRETE Cl/ Wcement (%)	
		Top	Bottom	Top	Bottom
0.300	2.500	1.718	1.611	1.121	1.108
	7.500	0.575	0.472	0.366	0.371
	12.500	0.153	0.118	0.030	0.033
	17.500	0.000	0.000	0.000	0.000
	22.500	0.000	0.000	0.000	0.000
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.400	2.500	3.109	2.916	1.780	1.518
	7.500	1.476	1.224	0.768	0.632
	12.500	0.505	0.416	0.218	0.167
	17.500	0.131	0.068	0.032	0.021
	22.500	0.000	0.000	0.000	0.000
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.500	2.500	5.036	3.816	2.934	2.417
	7.500	2.839	2.108	1.556	1.329
	12.500	1.450	1.018	0.831	0.717
	17.500	0.639	0.459	0.219	0.188
	22.500	0.273	0.108	0.041	0.058
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.600	2.500	5.831	5.264	3.774	3.248
	7.500	3.678	3.237	2.269	2.281
	12.500	2.312	2.086	1.485	1.176
	17.500	1.603	1.407	0.754	0.684
	22.500	0.909	0.714	0.322	0.261
	27.500	0.439	0.413	0.066	0.053
	32.500	0.133	0.112	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.700	2.500	6.525	5.975	4.384	3.564
	7.500	4.722	4.211	3.162	2.647
	12.500	3.086	2.828	2.200	1.681
	17.500	2.150	1.908	1.265	1.061
	22.500	1.705	1.152	0.679	0.549
	27.500	0.967	0.590	0.306	0.298
	32.500	0.483	0.273	0.098	0.089
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000

Table A5: Shows The Total Chloride Concentration at 5-month in Soaking Test.

W/C	Depth (mm)	(NORMAL) CONCRETE Cl/ Wcement (%)		(SCC) CONCRETE Cl/ Wcement (%)	
		Top	Bottom	Top	Bottom
0.300	2.500	3.359	3.247	2.400	2.386
	7.500	1.790	1.739	1.164	1.111
	12.500	0.515	0.482	0.284	0.246
	17.500	0.087	0.093	0.000	0.000
	22.500	0.000	0.000	0.000	0.000
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.400	2.500	6.338	4.423	5.098	3.156
	7.500	2.882	2.080	2.550	1.800
	12.500	1.620	1.246	1.406	1.092
	17.500	0.687	0.413	0.484	0.452
	22.500	0.142	0.000	0.098	0.080
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.500	2.500	6.759	5.376	5.923	3.557
	7.500	4.063	3.659	3.542	2.589
	12.500	2.646	2.237	2.232	1.720
	17.500	1.555	1.310	1.253	0.674
	22.500	0.908	0.672	0.556	0.106
	27.500	0.357	0.122	0.192	0.054
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.600	2.500	7.871	6.368	6.742	5.599
	7.500	5.777	4.239	4.796	3.746
	12.500	3.663	3.306	3.186	2.844
	17.500	2.730	2.313	2.117	1.798
	22.500	1.856	1.697	1.394	1.138
	27.500	1.138	1.034	0.803	0.626
	32.500	0.735	0.602	0.502	0.389
	37.500	0.443	0.355	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.700	2.500	8.306	7.641	7.410	6.585
	7.500	5.824	5.418	5.108	3.916
	12.500	4.723	4.020	3.852	3.577
	17.500	3.709	3.382	3.080	2.554
	22.500	2.953	2.460	2.040	2.291
	27.500	1.992	1.745	1.579	1.658
	32.500	1.687	1.144	0.960	1.234
	37.500	1.248	0.740	0.000	0.000
	42.500	0.462	0.393	0.000	0.000
	47.500	0.000	0.000	0.000	0.000

Table A6: Shows The Total Chloride Concentration at 5-month in Fog Test.

W/C	Depth (mm)	(NORMAL) CONCRETE Cl/ Wcement (%)		(SCC) CONCRETE Cl/ Wcement (%)	
		Top	Bottom	Top	Bottom
0.300	2.500	2.449	2.336	1.579	1.479
	7.500	1.043	0.881	0.524	0.504
	12.500	0.328	0.255	0.058	0.052
	17.500	0.000	0.000	0.000	0.000
	22.500	0.000	0.000	0.000	0.000
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.400	2.500	4.352	4.020	3.138	2.608
	7.500	2.140	1.713	1.609	1.376
	12.500	1.109	0.820	0.860	0.542
	17.500	0.259	0.300	0.156	0.144
	22.500	0.000	0.000	0.000	0.000
	27.500	0.000	0.000	0.000	0.000
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.500	2.500	6.277	4.226	4.035	2.994
	7.500	3.732	2.156	2.371	1.900
	12.500	2.610	1.950	1.618	1.298
	17.500	1.344	0.937	0.753	0.472
	22.500	0.697	0.498	0.305	0.153
	27.500	0.227	0.099	0.066	0.022
	32.500	0.000	0.000	0.000	0.000
	37.500	0.000	0.000	0.000	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.600	2.500	7.125	5.046	5.101	3.540
	7.500	5.166	3.534	3.080	2.648
	12.500	3.514	2.650	2.487	1.851
	17.500	2.186	1.917	1.512	1.527
	22.500	1.565	1.387	0.812	0.654
	27.500	1.067	0.896	0.526	0.286
	32.500	0.549	0.419	0.182	0.053
	37.500	0.289	0.218	0.056	0.000
	42.500	0.000	0.000	0.000	0.000
	47.500	0.000	0.000	0.000	0.000
0.700	2.500	7.574	5.813	5.868	4.366
	7.500	5.577	4.288	3.984	3.219
	12.500	4.483	3.475	3.012	2.361
	17.500	3.640	2.550	2.332	1.989
	22.500	2.820	1.681	1.649	1.345
	27.500	1.775	1.106	1.262	0.853
	32.500	1.375	0.632	0.728	0.457
	37.500	0.892	0.325	0.221	0.188
	42.500	0.453	0.169	0.000	0.000
	47.500	0.000	0.000	0.000	0.000

Appendix B: Tables show the diffusion coefficient
of concrete

Appendix B: Shows Diffusion Coefficients of concrete for 1,3 and 5 months Testing

Soaking Test					Fog Test				
1-month	Top Surface		Bottom Surface		1-month	Top Surface		Bottom Surface	
w/c	Normal	SCC	Normal	SCC	w/c	Normal	SCC	Normal	SCC
0.3	1.296	1.149	1.168	0.902	0.3	1.082	0.700	0.920	0.683
0.4	2.155	1.516	1.787	1.733	0.4	1.359	0.873	1.239	0.971
0.5	3.435	2.764	2.970	2.245	0.5	2.704	2.461	2.762	2.173
0.6	4.202	3.399	3.932	3.515	0.6	4.095	3.825	3.308	3.081
0.7	6.111	4.833	5.307	4.451	0.7	5.424	4.624	5.137	4.333
3-month	Top Surface		Bottom Surface		3-month	Top Surface		Bottom Surface	
w/c	Normal	SCC	Normal	SCC	w/c	Normal	SCC	Normal	SCC
0.3	0.724	0.642	0.872	0.526	0.3	0.618	0.468	0.543	0.484
0.4	1.273	1.181	1.335	1.253	0.4	1.047	0.825	0.864	0.765
0.5	2.159	1.653	2.150	1.872	0.5	1.867	1.495	1.655	1.586
0.6	3.467	2.662	3.377	2.914	0.6	3.393	2.486	3.261	2.717
0.7	5.585	4.578	4.600	4.341	0.7	5.159	3.969	4.365	4.125
5-month	Top Surface		Bottom Surface		5-month	Top Surface		Bottom Surface	
w/c	Normal	SCC	Normal	SCC	w/c	Normal	SCC	Normal	SCC
0.3	0.637	0.560	0.652	0.515	0.3	0.506	0.301	0.430	0.304
0.4	0.869	0.886	0.862	1.137	0.4	0.784	0.810	0.695	0.758
0.5	1.782	1.554	1.828	1.597	0.5	1.670	1.431	1.640	1.407
0.6	3.151	2.404	3.276	2.762	0.6	2.717	2.315	3.012	2.417
0.7	5.110	3.773	4.477	4.266	0.7	4.646	3.663	4.121	3.997

Appendix C: The aggregate gradation by sieve test

Table C-1: Crushed sand gradation

sieve size (mm)	W sand	% retained	% retained acc.	% passing
10	0.00	0.00	0.00	100.00
5	0.70	0.12	0.12	99.88
2.5	166.00	27.67	27.78	72.22
1.2	331.50	55.25	83.03	16.97
0.6	36.30	6.05	89.08	10.92
0.3	28.80	4.80	93.88	6.12
0.15	20.20	3.37	97.25	2.75
0	16.50	2.75	100.00	0.00
total	600.00	100.00		

Table C-2: Sea sand gradation

sieve size (mm)	W sand	% retained	% retained acc.	% passing
10	0.00	0.00	0.00	100.00
5	49.20	8.20	8.20	91.80
2.5	161.60	26.93	35.13	64.87
1.2	275.20	45.87	81.00	19.00
0.6	39.70	6.62	87.62	12.38
0.3	31.70	5.28	92.90	7.10
0.15	24.00	4.00	96.90	3.10
0	18.60	3.10	100.00	0.00
total	600.00	100.00		

Table C-3: Large size gravel

G_{max} = 20 mm.

sieve size (mm)	W gravel	% retained	% retained acc.	% passing
80	0.00	0.00	0.00	100.00
40	0.00	0.00	0.00	100.00
20	151.00	2.95	2.95	97.05
13.2	3112.00	60.86	63.82	36.18
10	1774.00	34.70	98.51	1.49
5	58.00	1.13	99.65	0.35
2.5	18.00	0.35	100.00	0.00
total	5113.00	100.00		

Table C-4: Small size gravel

G_{max} = 10 mm.

sieve size (mm)	W sand	% retained	% retained acc.	% passing
80	0.00	0.00	0.00	100.00
40	0.00	0.00	0.00	100.00
20	0.00	0.00	0.00	100.00
10	628.12	20.94	20.94	79.06
5	2371.88	79.06	100.00	0.00
2.5	0.00	0.00	100.00	0.00
total	3000.00	100.00		

Appendix D: The total chloride ion concentration at inner surface of concrete
(kg/m³)

Appendix D-1: Shows The Total Chloride Concentration at The Inner Surface for Soaking Test.

1-month W/C	Initial solution Cl/ Wcement (%)	Initial solution Cl/ Wcement (%)	(NORMAL) CONCRETE Cl/ Wcement (%)		(SCC) CONCRETE Cl/ Wcement (%)	
	(Normal concrete)	(SCC)	Top	Bottom	Top	Bottom
0.30	25.18	20.19	4.17	3.93	2.59	2.06
0.40	33.33	26.65	9.30	7.29	7.41	6.15
0.50	41.48	33.12	17.51	14.54	12.95	10.57
0.60	49.63	39.59	24.96	20.71	21.28	16.86
0.70	57.78	46.06	38.99	29.78	26.97	20.60
3-month						
0.30	25.18	20.19	7.32	6.48	5.88	4.61
0.40	33.33	26.65	14.85	12.28	12.21	10.58
0.50	41.48	33.12	30.63	16.80	27.77	17.57
0.60	49.63	39.59	44.03	32.32	41.19	27.58
0.70	57.78	46.06	67.51	56.88	56.59	46.95
5-month						
0.30	25.18	20.19	12.65	11.75	9.41	8.32
0.40	33.33	26.65	28.47	19.87	22.90	15.71
0.50	41.48	33.12	43.07	32.01	37.75	21.18
0.60	49.63	39.59	70.00	47.26	59.96	45.30
0.70	57.78	46.06	92.23	75.46	73.18	65.03

Appendix D-2: Shows The Total Chloride Concentration at The Inner Surface for Fog Test.

1-month W/C	Initial solution Cl/ Wcement (%)	Initial solution Cl/ Wcement (%)	(NORMAL) CONCRETE Cl/ Wcement (%)		(SCC) CONCRETE Cl/ Wcement (%)	
	(Normal concrete)	(SCC)	Top	Bottom	Top	Bottom
0.30	25.18	20.19	2.98	2.27	1.50	1.25
0.40	33.33	26.65	6.27	4.89	4.84	3.63
0.50	41.48	33.12	11.13	9.26	9.40	7.28
0.60	49.63	39.59	17.57	14.14	13.69	11.63
0.70	57.78	46.06	26.53	20.80	22.12	18.00
3-month						
0.30	25.18	20.19	5.07	4.14	3.12	2.92
0.40	33.33	26.65	11.70	9.81	6.21	4.93
0.50	41.48	33.12	25.07	17.14	13.85	11.41
0.60	49.63	39.59	39.98	31.34	25.88	19.34
0.70	57.78	46.06	52.79	44.35	35.47	26.45
5-month						
0.30	25.18	20.19	8.24	6.16	4.96	3.90
0.40	33.33	26.65	18.64	17.22	12.31	10.68
0.50	41.48	33.12	40.00	23.61	24.02	16.73
0.60	49.63	39.59	57.65	37.45	41.27	26.27
0.70	57.78	46.06	84.10	51.70	57.95	43.11

Appendix E: Verification data collected from the references

Mix proportion

	w/c	cement	water	20mm agg.	10mm agg.	sand	sp	Average D
Name		(kg/m ³)	(cm ² /yr)					
Ref. 13	0.27	500	135	426	851	548	7.3	4.85
Ref. 13	0.33	500	165	419	837	539	4.7	9.88
Ref. 13	0.39	500	195	410	819	527	2.7	28.53
Ref. 13	0.45	500	225	403	805	518	0	38.56
Ref.14	0.26	660	156	1100	-	620	1.8	2.40
Ref.14	0.3	550	165	1120	-	640	1.5	2.60
Ref.14	0.34	500	170	1150	-	640	1	5.50
Ref. 2(28d)	0.5	350	175	481	475	866	-	2.59
Ref. 2(98d)	0.5	350	175	481	475	866	-	2.32
Ref. 2(182d)	0.5	350	175	481	475	866	-	1.84
Ref. 2(378d)	0.5	350	175	481	475	866	-	1.99
Ref. 2(588d)	0.5	350	175	481	475	866	-	1.72
Ref. 17	0.5	390	195	787	-	876	-	1.15

Note: The average D was computed from the total chloride concentration curve from the references by the concept used in this paper.