# Computational Model for Chloride Concentration at Surface of Concrete Under Actual Environmental Condition

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# Abstract

The integrated computational model in this study is to calculate the chloride concentration in concrete under actual environmental conditions in the atmosphere. The integrated model consists of 3 minor models for understanding the mechanisms of environmental parameters influencing the chlorides attack to concrete structures.

(1) The first model is considered as the study on airborne chlorides formation and transportation. The simplification model on the airborne chlorides formation and flying upward to the atmosphere is proposed. In sequence, the model of airborne chlorides transportation to the surface of concrete is further simulated. The wind speed is one of main parameters in airborne chlorides formation and transportation. The calculated result in this model is the accumulative airborne chlorides in a time interval. In this model is verified by the measurement of airborne chlorides by Public Work Research Institute, 1984-1986.

(2) The second model is the calculation of accumulative chloride concentration on surface of concrete. The related parameters in this model are amount of airborne chlorides, surface roughness of concrete, types of structural members and rain. Rain effect is thought as the largest effect on the removal of chloride concentration on the surface of concrete. In the verification of this model, the experimental observation of chloride concentration on surface of existing structures in Kochi prefecture with time history is compared.

(3) The third model is the computation for chloride concentration in concrete. The distribution of chloride concentration on surface of concrete obtained from the second model is used as the input of this model. The computation of chloride concentration in concrete is calculated by DuCOM program. The integrated model of these 3 steps of calculation is proved by comparing the monitoring data of chloride concentration of existing structures from Public Work Research Institute 2000.

Table of Contents

# List of Tables

## List of Figures

# CHAPTER 1

# Introduction

## 1.1 General

The asset management and sustainable construction is the aims of the future construction projects. For achieving management system, the service life-span prediction model is necessary due to the degradation of structures by the ambient environmental attack. One of the most noteworthy environmental problems on the concrete structure is chloride attack resulting corrosion of steel bars. A simple schematic work on the service life prediction and maintenance [2,27] is shown as in **Fig1.1**. The model of life-span simulation due to the chloride attack only expresses in this study. It is shown that the infrastructure management on the structures near seashore needs a model that can predict the mechanism of chloride attack to concrete.

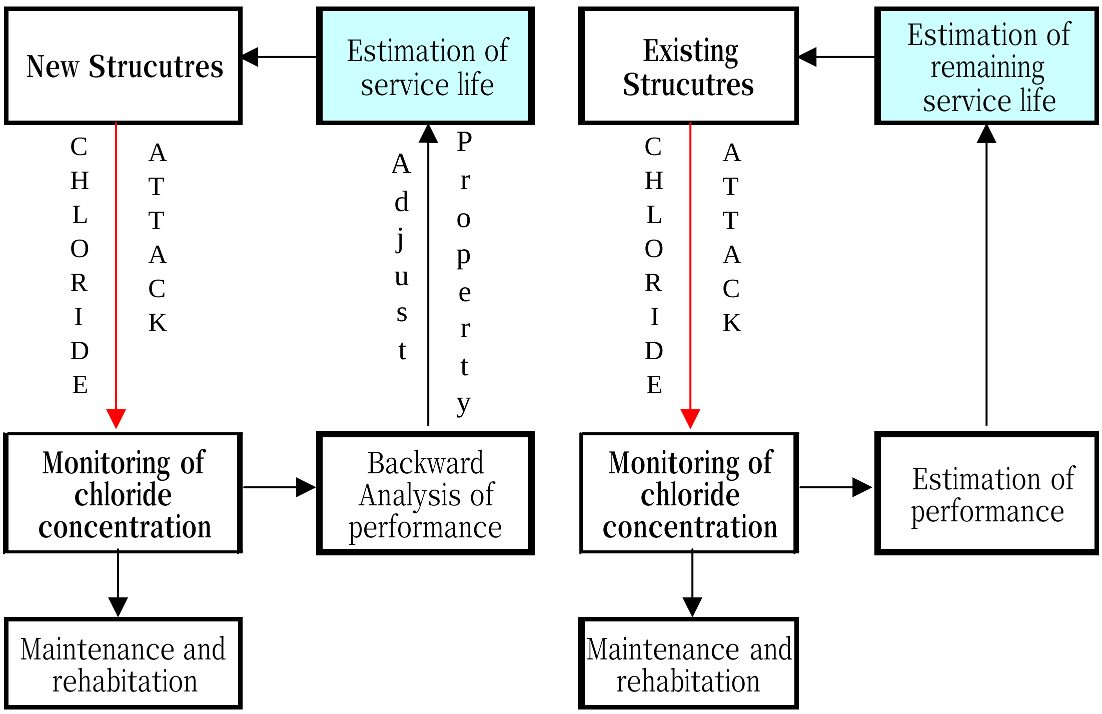
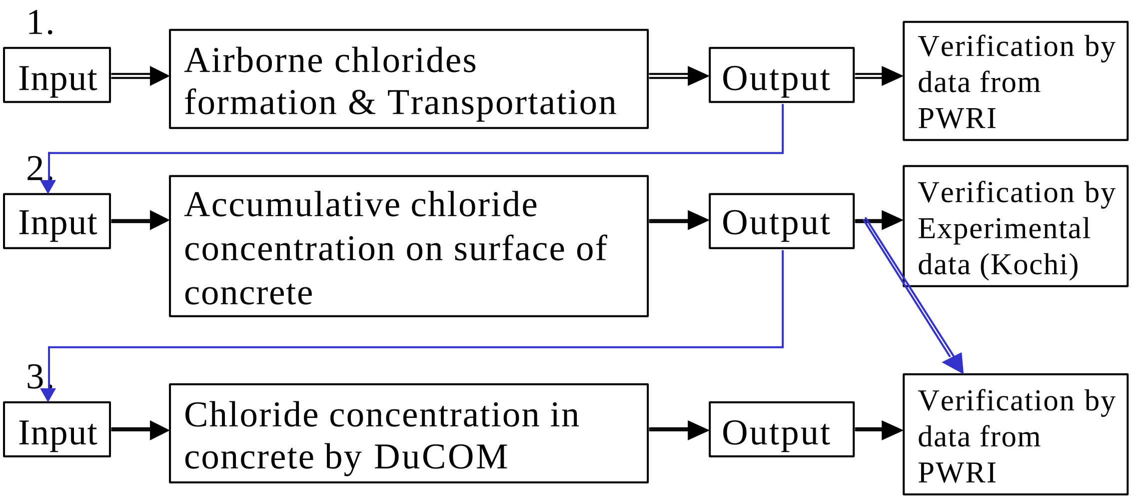



**Fig.1.1:** A simple Schematic of infrastructure management [2].

Life-span prediction of some infrastructures is necessary for durability, reliability and safety performances. The sustainable development of infrastructures is required to maintain their performances over the long life. Maekawa, et al developed a life-span simulation model named DuCOM and COM3 for predicting overall structural behaviors [3-5]. The 3-D multi-scale coupled system is built on the thermo-hydro physics coded by DuCOM for early-aged concrete and nonlinear mechanics FEM coded by COM3 for seismic performance assessment of reinforced concrete. In the mechanic actions such as ground acceleration, gravity, temperature and shrinkage effects simulates in the COM3 section. The concrete durability by environmental attacks can be simulated by DuCOM in any input data of environmental conditions. Therefore the analysis of chloride transport by DuCOM required the boundary condition of the ambient chloride contents. At this moment, there is none of the method to create such a boundary condition for a structure exposed in the atmosphere. In considering the chloride attack in concrete, time-step simulation model is necessary for calculating the amount of chloride penetration into concrete with time dependency. DuCOM is one of the appropriate computational program for analyzing chloride transport behavior. Whenever, the appropriate boundary condition is known, DuCOM is able to simulate the chloride transport in concrete. Thus the study of chloride transport in the atmosphere to the boundary surface layer under actual environment is required as shown in **Fig.1.2**. In an actual environmental condition, a particular location has a typical weather and a variety of the wetting-drying cycles. The wetting-drying cycle is one of the factors that influence the rate of chlorides penetration in concrete [6]. It is necessary to make the parametric study on the main environmental parameters, such as the wetting-drying cycles, relative humidity and amount of airborne chlorides. From preliminary study of the wetting-drying cycles and the ambient relative humidity cannot clarify the severity of the locations around Japan[4)]. In sequence, other parameters are simulated on how much each parameter has an effect on the chloride transport in concrete. The most effective parameter is declared as amount of airborne chloride available in a specific distance from seashore. It is also necessary to know the airborne chlorides at the location of the structure for use as complementary for chloride transport through concrete. The airborne chlorides in the atmosphere are able to classify the severity in each location around Japan. The airborne chlorides in various distances from the seashore were collected around Japan by 'Public Works Research Institute' [1]. However, the proper simulation based on this database is still in the progress by many researchers. In general discussion, the relationships among the available airborne chlorides, wind speed & directions, surface conditions of concrete, and amount of absorbed chlorides at surface of concrete are necessary for quantitative identification. Thus, a systematic computational model in analyzing environmental effect on the chlorides penetration in concrete is the most required in recent times.

The systematic computational model of the chloride attack in concrete structure is divided into three sub-models. The first sub-model of the chloride attack has to be considered starting from the seashore just after forming of breaking water. The characteristic of coastline, landscape, seashore slope, and artificial landscape are important to regard as the supplement of airborne chlorides at seashore. Then the transportation of airborne chlorides from breaking seawater through the atmosphere to the surface of concrete is extended. The second sub-model is the analysis on how many airborne chlorides accumulate on surface layer of concrete. After all, the computation on chloride transport in concrete is to obtain the chloride concentration along the covering depth of concrete. As a result, the systematic computation on real behavior with actual environments is succeeded.




| | | |
|---|---|---|
| **1.** | **Input** = U, distance, offshore topography | **Output** = $C_{air}$ (mdh) |
| **2.** | **Input** = $C_{air}$, concrete roughness, rain, wind, member types | **Output** = Time dependent $C_o$ |
| **3.** | **Input** = Time dependent $C_o$, w/c | **Output** = Cl concentration in concrete |

**Fig.1.2** Schematic of integrated simulation of chloride transport in concrete structures

## 1.2 State of Problems

As mentions above, the integrated multi-scale computational program named DuCOM had developed for support the simulation of chloride transport in any environmental conditions. DuCOM can simulate the chloride distribution in concrete in the severe environmental condition as submerged and tidal zones. The chloride attack on the structure in the atmosphere is able to simulate if the boundary condition and environmental effect were known. Thus, the analysis of chloride concentration by DuCOM requires an appropriate input data under actual environment. At present, there is no a proper method to simulate the actual environment and create a boundary condition for analysis by DuCOM. Moreover, the creation of the boundary condition at surface layer of concrete is complicated due to distribution of weather.

The environmental factors of wind speed, wind direction, temperature, RH, airborne chloride and rain are mainly factors on accumulative chloride concentration at surface of concrete. Wind speed is thought as the driven force for transporting airborne particles to the surface of a structure. This medium is due to the directions, which has possibility to reach their destination. Temperature and RH are the nature pointing out the wetting-drying ratio and have effect on the penetration in concrete. Airborne chloride formation is a key factor to know how much airborne is formed at seashore and ready to transport whenever wind blows. Airborne chloride particles are supplied by the formation after wave breaking at seashore and wind speed. Rain is the main factor to reduce the amount of chlorides on the surface of concrete. At the same time, the increment of the degree of saturation allows the diffusion mechanism to occur rapidly. The equations for calculating the quantitative effects of the parameters are still not existed. The problems have to be solved systematically and it is time to do it immediately.

## 1.3 Objectives of Study

The objectives of this study are shown in **Fig1.1** in a macro scale. The necessity of this study provides the systematic life-span simulation under actual environments. In order to succeed this aim, the computational model for the chloride formation, transportation and accumulation on concrete surface are necessary in order to obtain the chloride distribution in concrete under atmospheric environment. Next, the computational model can be used for the development of recent design method. This is also fulfilling the design of the chloride distribution in concrete in any locations, specific types. Later on, the advantage of model is able to use as the prediction of the service life simulation in the field of asset management.

Without this model, JSCE specification is a prediction model, which can be used to predict the service life. However the model in JSCE specification is a conservative method, this is only parameter of distance from seashore as the main parameter. From the monitoring of the existing structures in any locations around Japan, the chloride attack depends on the particular environmental conditions. As the result, the prediction of service life has low precision and high error leading to inefficient management system. For solving this problem, the new prediction proposed in this study can be applied instead of the present method. The improvement of the model helps the management and monitoring system being better decisive factor.

Afterward, the new service life prediction model is pertinent for the development on this field. The individual analysis of the structures or the integration of the entire structural situation is a supporting tools in the asset management system both sections of micro and macro economies.

# CHAPTER 2

# Literatures

## 2.1 Airborne chloride transportation in the atmosphere

In 1983, Japan Roads Association [7] started monitoring the structural conditions about chloride attack and cracking provision. The selection of investigated structures is mostly aging up to 50 years. The limitation of the investigated structures is within the distance 500m from seashore, Bridge with span larger than 15 m, Constructed structure before year 1972. The RC and PC structures are examined totally 920 structures around Japan. The **Fig.2.1.1** shows the investigation of soundness condition of the structure around Japan. This figures include various ages of structures, thus the details of each investigated structures are necessary. Nevertheless, the consideration of time history for overall investigated structures is able to elucidate the severity of each zone. The summarization of the severity was proposed as shown in **Fig. 2.1.2**.

**Table 2.1.1:** Classification of severity of chloride attack

| Zone | Locations | Distance from seashore | SEVERITY |
|---|---|---|---|
| A | Okinawa | Up to 100m from seashore | I |
| | | Other distances | II |
| B | Japan Sea Coastline | Up to 100m from seashore | I |
| | | 100-200 m | II |
| | | 200-300 m | III |
| C | Others | Splash zone | I |
| | | Up to 100m from seashore | II |
| | | 100-200 m | III |

The investigation of the airborne measurement [1,7] in various locations has been organized followed JIS Z2381 [28]. The apparatus is the steel plate of 10x10cm dimensions. Windblown transports airborne chlorides to attach with the steel plate. The collection is done for 1-month interval for enough noticeable quantity. The roof is also set for protecting the rain effect to the removal of airborne chloride. The total airborne chlorides were measured and calculated the amount in $mg/dm^2$/month. The average chloride content is calculated by

$$C_{air} = \frac{CL \times W}{t \times A} \qquad (2.1.1)$$

where, $C_{air}$ is daily average of airborne chloride ($mg/dm^2$/day)

CL is collected airborne chloride (mg/ml)

W is amount of water used for washing out from steel plate (ml)

t is exposure time (days)

A is specific surface area (= $1dm^2$)

The airborne chloride observed value with the distance from seashore is the exponential function with the attitude of airborne chloride content at seashore as shown in **Eq.2.1.2**.

$$C_{air} = C_{o,air}.e^{-1.55\sqrt{\frac{l}{1000}}} \qquad (2.1.2)$$

where, $C_{air}$ is daily average airborne chlorides ($mg/dm^2$/day)

$C_{o,air}$ is daily average of airborne chloride at seashore ($mg/dm^2$/day)

$l$ is distance from seashore (m)

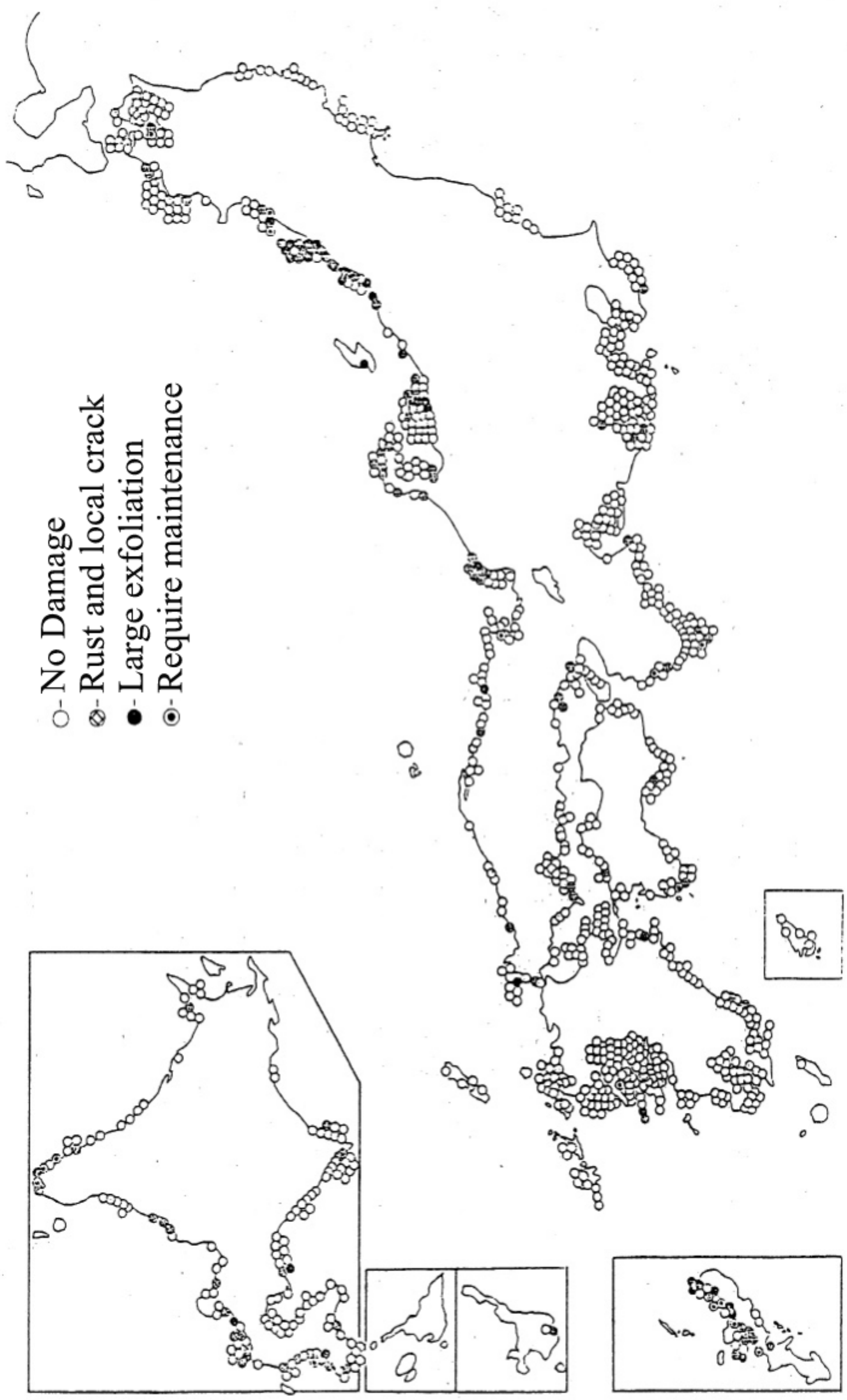



Fig.2.1.1: The investigation of soundness of strucutres around Japan

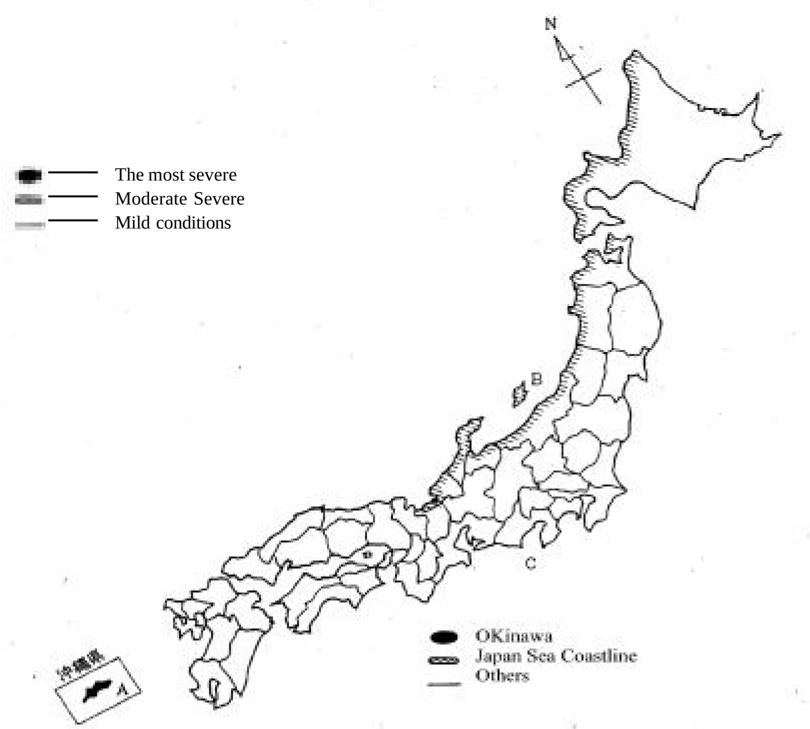



**Fig.2.1.2:** Level of severity in the particular region around Japan

Another relationship of airborne chloride with distance from seashore was purposed later by PWRI [1] in 1985. The overall investigation of airborne chloride around Japan was organized and observation was done during 1984-1986 in monthly data. The level of airborne chlorides around Japan is shown in **Fig.2.1.4**, and the relationship is averaged by **Eq. 2.1.3**.

$$C_{air} = C_{air,1}\,(0.001 * l)^{-0.6} \qquad (2.1.3)$$

where, $C_{air,1}$ is airborne chlorides at 1 km from seashore (mg/dm$^2$/day)

The consideration of wind speed and wind direction is developed subsequently, but a precise function between wind speed and airborne chlorides is complicated.

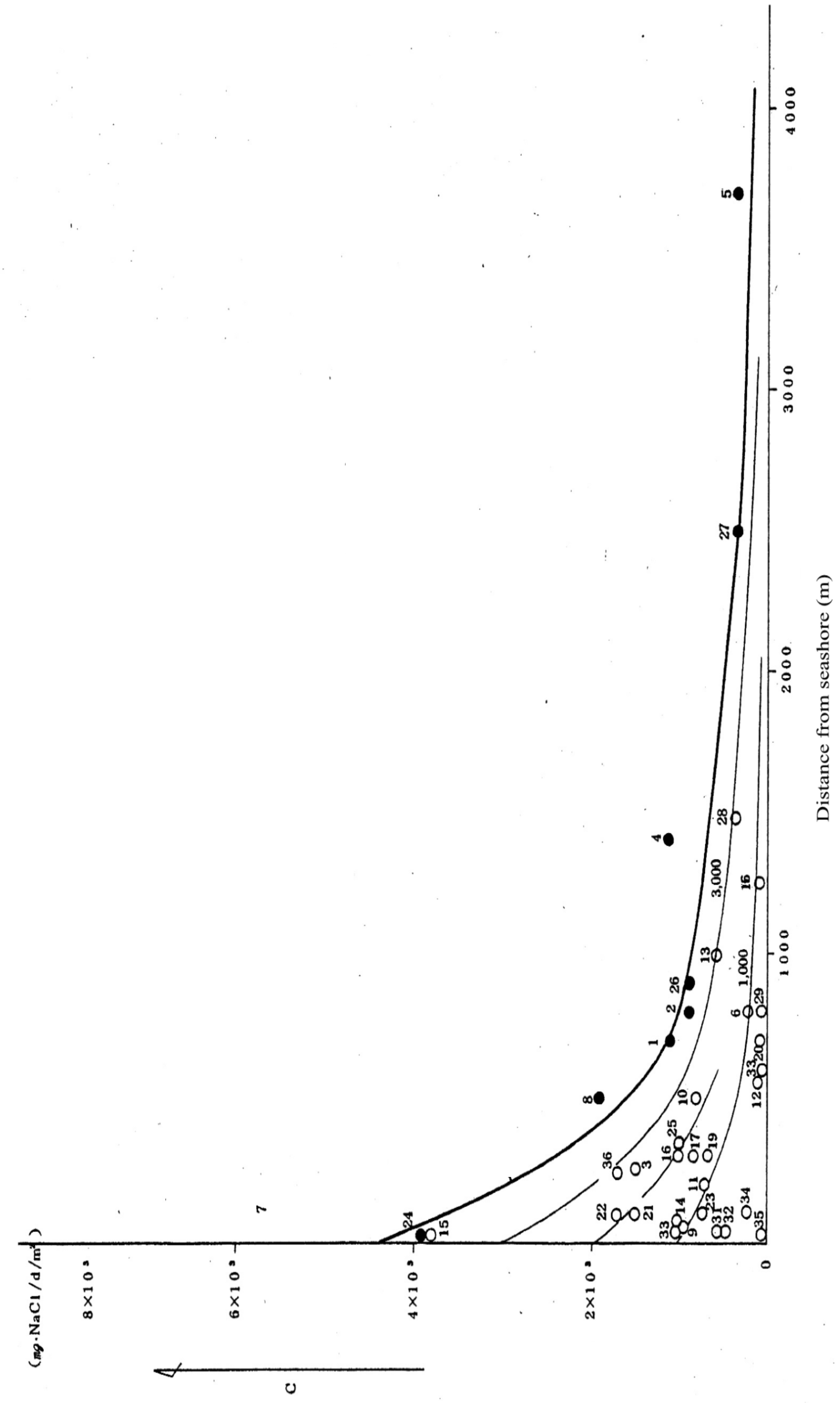



Fig.2.1.3: The investigation of airborne chloride [7]

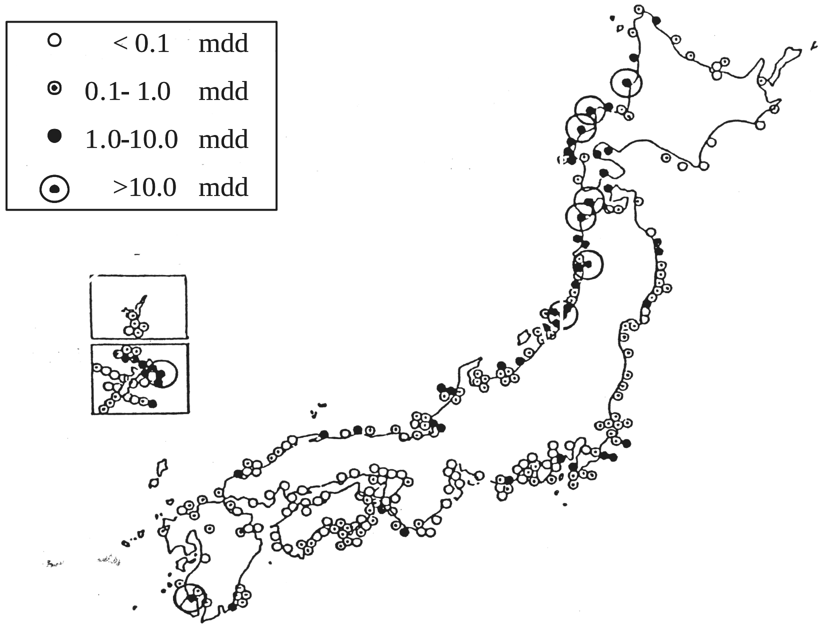



**Fig.2.1.4**: The investigation of airborne chlorides by PWRI [1]

Many relationships were purposed in a high scatter. From literatures [1,8,9,10], the amount of airborne chlorides in a distance is thought as the function of the third power of wind speed, and wind direction as shown below,

$$C_{air} = f\,(U^3, r) \qquad (2.1.4)$$

where, $C_{air}$ is daily average airborne chloride (mg/dm$^2$/day)

U is wind speed (m/s)

r is wind ratio in landward direction

The regression analysis of a numbers of experimental results was proposed as a choice for analyzing wind speed relationship [19]. The formulas do not show a particular function, but they were recommended by classifying the data into

- Low-scale of airborne chlorides

$$C_{air} = 0.0515.r.\ U^{2.27} \qquad R=0.488 \qquad (2.1.5)$$

- Large-scale of airborne chlorides

$$C_{air} = 0.0150.r.\ U^{3.29} \qquad R=0.671 \qquad (2.1.6)$$

where, R is regression value

Wind speed, wind direction and distance from seashore were examined by many literatures. Conversely, the amount of airborne chlorides cannot explain how it affects to the chloride transportation. The medium to link between the available chloride ions and the penetration into concrete should be analyzed.

## 2.2 Computational program on chloride transport in concrete

The three-dimensional multi-scale couple system of thermo-hygro interaction is constructed and coded by DuCOM. DuCOM is a simulation tool for early aged concrete in basic hardened concrete properties with time scale. The Integrating of DuCOM with the non-linear mechanics FEM coded by COM3 described in **Fig.2.2.1** [5] for seismic performance of reinforced concrete conducts the durability simulation considering with both damage by loads and weather actions. The scheme of this simulation model of chloride transport in concrete named DuCOM involves the incorporation with mainly,

2.2.1 Cement hydration and thermal conduction [3]

2.2.2 Pore structure formation and moisture equilibrium and transport [3]

2.2.3 Free/bound chloride equilibrium and transport [4]

2.2.4 Carbonation and dissolved carbon dioxide migration [4]

2.2.5 Corrosion of steel and dissolved oxygen transport [4]

Mention in the **Section 2.2.3**, the governing equations for chloride transport in cementitious materials by advective-diffusive phenomenon with time dependent are shown as

$$\partial(\phi.S.C_{cl})/\partial t + divJ_{cl} - Q_{cl} = 0 \qquad (2.2.1)$$

$$J_{cl} = (-\phi.S.D_{cl.}\nabla C_{cl}/\Omega) + \phi S.u.C_{cl} \qquad (2.2.2)$$

where, $\phi$ is porosity, S is degree of saturation,

$C_{cl}$ is free chloride concentration in pore solution (mol/l),

$J_{cl}$ is flux of chloride ion ($mol/m^2.s$),

$Q_{cl}$ is reduction of free chloride,

$D_{cl}$ is chloride ion diffusivity in pore solution phase ($m^2/s$),

$\Omega$ is tortuosity of pore as equal to $(\pi/2)^2$

Chloride transport in cementitious materials under actual conditions is an advection-diffusion phenomenon. Mass balance of free chlorides can be expressed **Eq.2.2.1** and **Eq.2.2.2**.

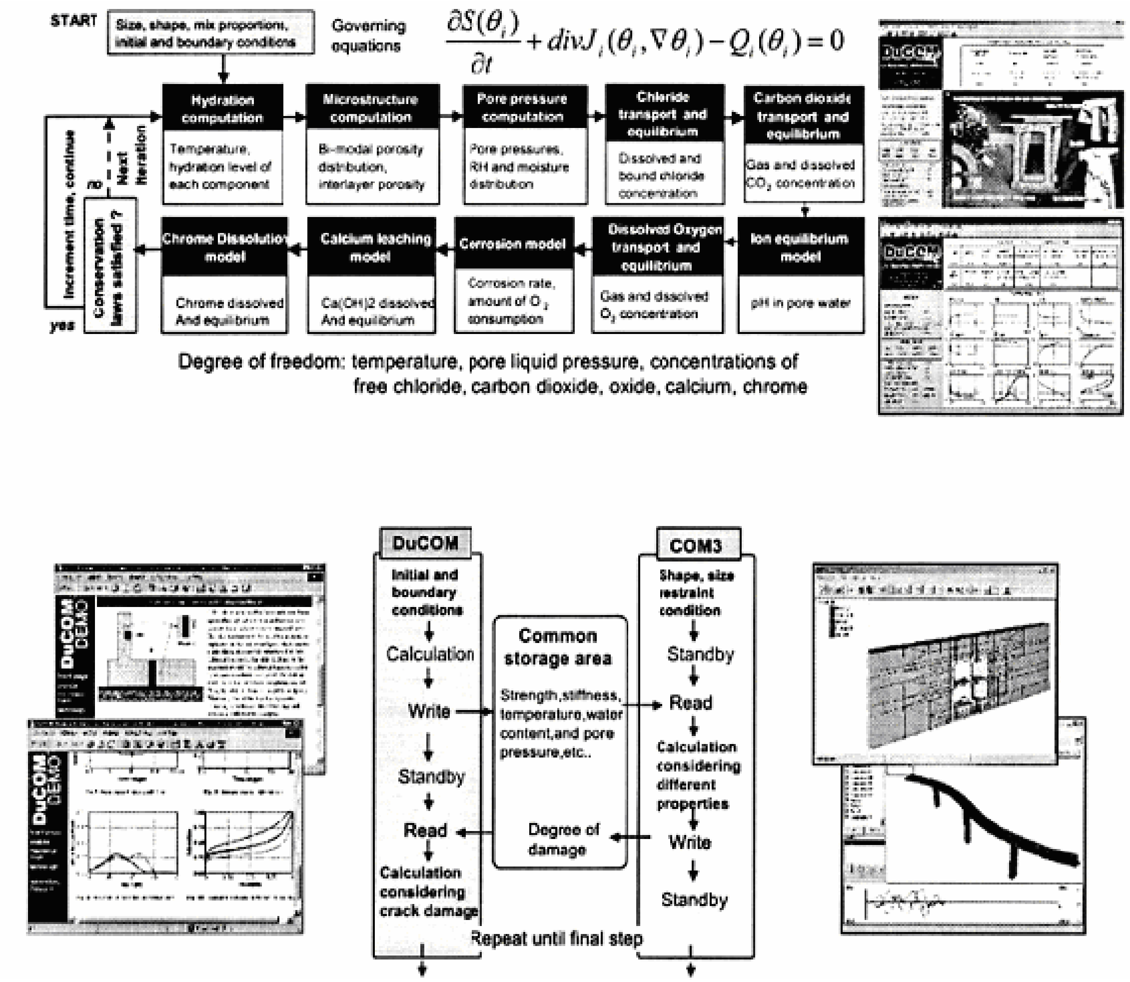



**Fig.2.2.1:** Integration of microphysics-DuCOM and macro-structural analysis-COM3 [5]

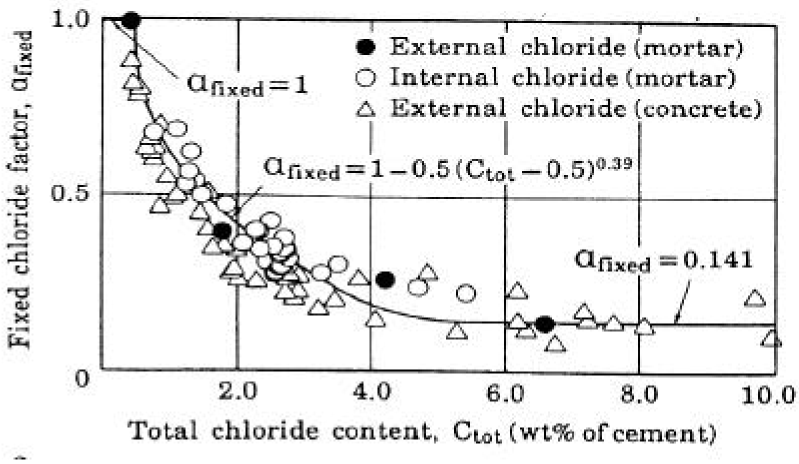



**Fig.2.2.2:** Relationship between total chloride content and fixed chloride factor [11]

Chlorides in cementitious materials have free and bound components. The bound chlorides are settled by reaction with aluminates and formed in quantitative value as in **Fig.2.2.2**. The bound chlorides were classified into 2 phases of adsorbed and chemically combined components. From the formulations, the total and free chlorides can be obtained whenever mix proportion, powder properties, curing, RH, temperature and ambient chloride concentration (mol/l) were set.

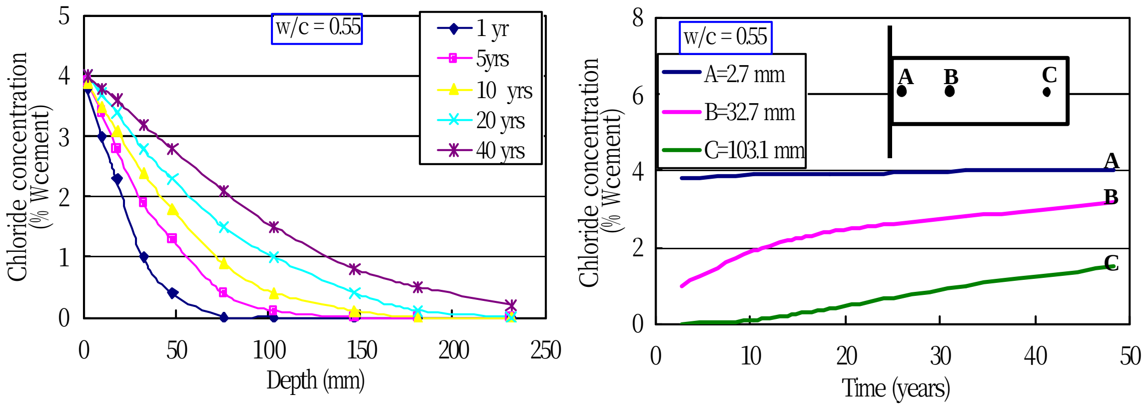
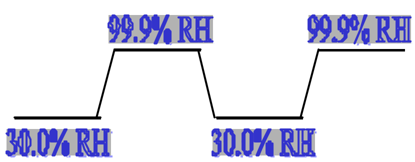



**Fig.2.2.3:** Example of chloride concentration in concrete submerged in 3% NaCl



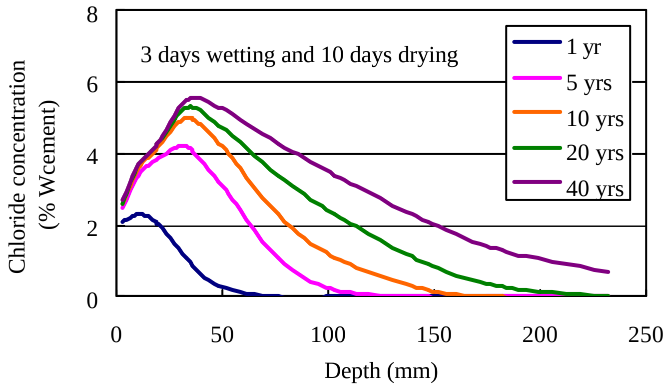




**Fig.2.2.4:** Example of chloride concentration in concrete in looping of 3-days wetting + 10-days drying

The diffusion and condensation expressed the mechanism of chloride transport in submerged conditions. Considering the constant boundary condition, the ambient chloride concentration is 3% of NaCl. In **Fig.2.2.3**, the analyzed results show time dependent chloride concentration in various depths. The chloride concentrations at surface from 1 year to 40 years are constant. This is explained by the constant boundary condition. The analysis is extent to the simulation of non-steady state of ambient condition on fluctuated RH. The advection affects by wetting-drying cycles, and the ratio of the cycles has a difference of inside concentration. The surface layer of chloride content at 2-3 cm from surface fluctuates due to wetting and drying periods. Wetting period leads the diffusion and advection become highly effective. Drying period causes the declination of chloride content and RH at surface layer, afterward the wetting can have a big influence of advection. At 2-3 cm from surface, chloride concentration is condensed higher than the value of boundary condition as shown in **Fig.2.2.4**.

## 2.3 Design Specification and investigation of existing structures

The investigation of deterioration and structural status was done around Japan by PWRI [12]. More than 2000 members were observed in various conditions of rust, corrosion, crack and spalling.152 members were examined the chloride concentration in concrete by coring the samples from non-reinforced section as shown in **Table.2.3.1**. Locations and structural types were classified in the table as well. 10 zones around Japan were divided for individual characteristic of weather conditions. 6 types of concrete structures were also categorized by crest structure, abutment, retaining wall, culvert, rivers structure and tunnel.

**Table2.3.1:** Investigation of structures in each location

| Structural types | Hokkaido | Tohoku | Kanto | Hokuriku | Chubu | Kinki | Chukoku | Shikoku | Kyushu | Okinawa | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Crest structure | 40 | 28 | 63 | 24 | 31 | 53 | 37 | 32 | 55 | 8 | 371 |
| Abutment | 40 | 38 | 65 | 24 | 38 | 52 | 40 | 31 | 54 | 8 | 390 |
| Retaining wall | 40 | 25 | 56 | 24 | 36 | 44 | 40 | 31 | 43 | 9 | 348 |
| Culvert | 40 | 35 | 64 | 24 | 34 | 53 | 39 | 27 | 48 | 6 | 370 |
| Rivers structure | 40 | 41 | 60 | 27 | 32 | 47 | 37 | 28 | 52 | 0 | 364 |
| Tunnel | 37 | 35 | 25 | 16 | 22 | 27 | 30 | 27 | 32 | 5 | 256 |
| Total | 237 | 202 | 333 | 139 | 193 | 276 | 223 | 176 | 284 | 36 | 2099 |

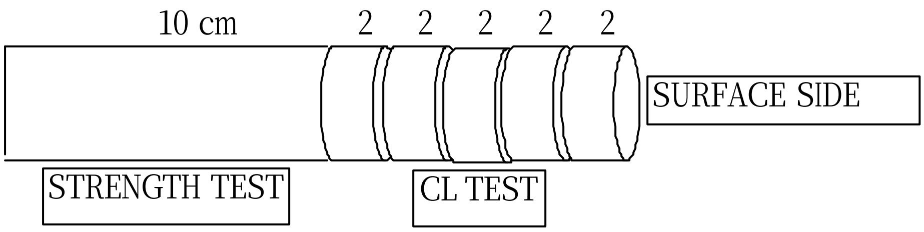



**Fig.2.3.1:** Concrete coring for chloride concentration test and strength test

The **Fig.2.3.1** shows the coring sample in the length longer than 200mm. 5 pieces of 2cm size were cut and tested for chloride concentration by averaging at middle of section. Thus, the average chloride contents express 5 positions of 1,3,5,7 and 9cm. Later section, 10cm depth was cut for strength test to evaluate the hardened properties of concrete. The observed values were compared with the results from Fick'2$^{nd}$ Law equation recommended by JSCE Specification, 2002 [13].

$$C(x,t) = Co\left(1 - erf\ \frac{x}{2\sqrt{D.t}}\right) + C(x,0) \qquad (2.2.3)$$

where, $C_{(x,t)}$ is chloride ions concentration at time t (kg/m$^3$)

$C_o$ is chloride ions concentration at surface of concrete (kg/m$^3$)

x is covering depth (cm)

D is apparent diffusion coefficient (cm$^2$/yr) t is exposure time (yrs)

$C_{(x,o)}$ is initial chloride ions concentration (kg/m$^3$)

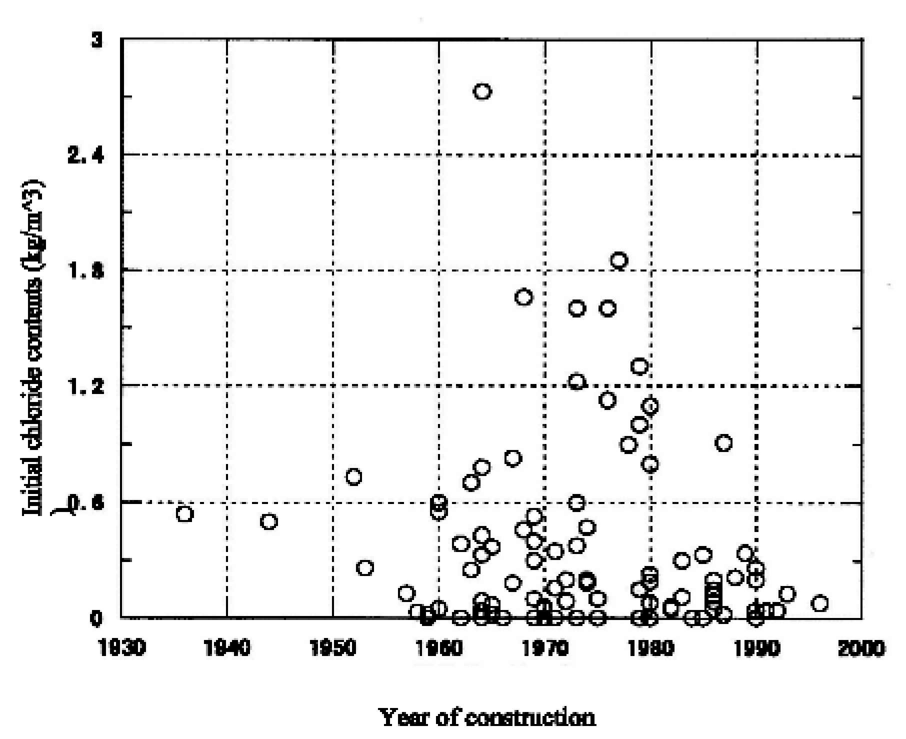



**Fig. 2.3.2:** Estimation of initial chloride concentration from the examination [12]

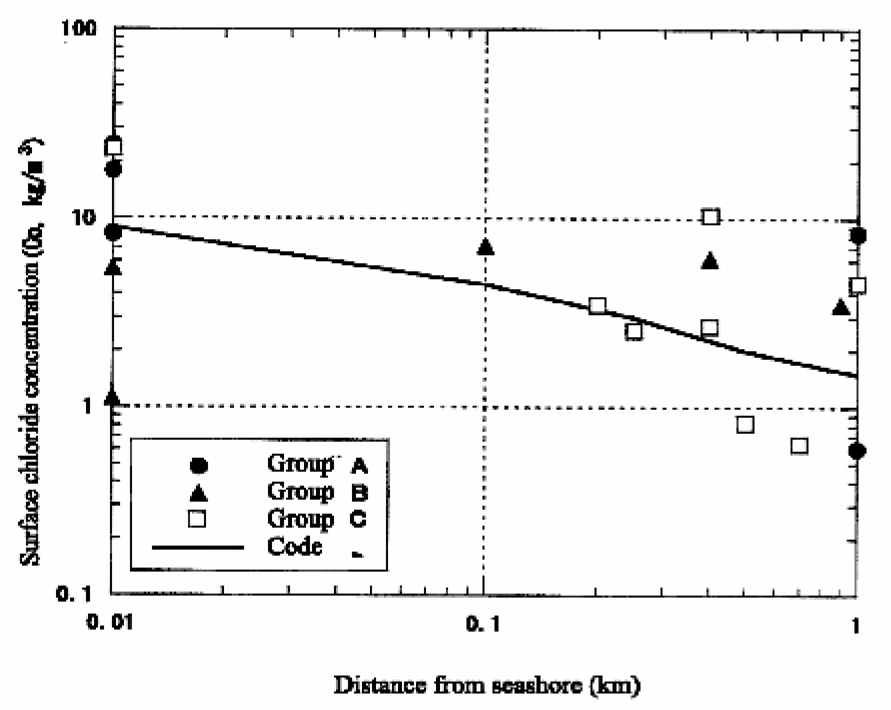



**Fig.2.3.3:** Surface chloride concentration and distance relationship.

The 152 structures were classified into 4 groups,

**Group A: Eq.2.2.1** fits to 5 investigated points to the calculation

**Group B:** Chlorides in the depth 0-2 cm is little smaller than the calculated value and other points are in trend

**Group C:** Chlorides in the depth 0-2 cm is dramatically smaller than calculated value and other points are in trend

**Group D:** Chlorides in the depth 0-2 cm and 2-4 cm are dramatically smaller than calculated value and other points are in trend

In **Fig.2.3.2**, the calculation of initial chloride concentrations in this investigation was plotted with the year of construction. In general of the structures constructed before 1985, the initial chloride concentration was observed at larger than 0.6 kg/m$^3$. The appendix A. shows the selected investigated data on the chloride concentration and the depth of carbonation. The data was selected due to the enough information in analysis only. The surface chlorides at 0-2 cm of the samples in group A, B and C were plotted with the relationship with distance from seashore. At the same time, the comparison with the recommended value in JSCE specification was done in log-scale. It expressed high dispersion more than two times difference. However this is necessary to find out the cause of deviated data from the real structures in a particular location.

# CHAPTER 3

# Computational model for chloride distribution under simple environmental conditions

## 3.1 Introduction

The purpose of this chapter is to investigate the mechanism of chlorides transport, especially focusing on the effect of wetting-drying conditions on the penetration. Basically, the movement of chloride ion into concrete is due to two main mechanisms; the diffusive movement caused by concentration differences of chlorides, and advective transport due to bulk suction of pore water. The moisture content or RH inside concrete subjected to an ambient environment, such as complex wetting-drying condition, does not have constant distribution throughout the depth. The surface region at 0-3 cm could have a fluctuation in terms of RH inside pore structure when it is subjected to wetting and drying conditions. Moreover, a value of an ambient RH also controls the rate of the chlorides penetration. Of course, properties of concrete, such as strength, porosity and its distribution, are used to determine how chloride ions behave in concrete. In this paper, the mechanisms of chloride movement under steady-state condition and several types of wetting-drying cycles are discussed. As usual of real environment, each season has a typical environmental condition and all of them have different wetting-drying cycles. At each location in Japan from East to West or from Hokkaido to Okinawa, the difference of environmental condition brings some difficulties to evaluate severity of chloride ions. The important point is to show some facts of the real mechanism of chloride movement as a basic knowledge to evaluate the effect on the chlorides transport in actual environments.

A numerical tool simulating concrete properties, such as the microstructure development has been proposed by Maekawa, et al [3]. Then the target of this technology has been widened by installing the chloride transport model [4]. The combination of these 2 models can simulate the development of microstructure and RH with time and the amount of total chloride ions concentration in each period. The software calculating the chloride ions concentration in concrete based on the above model is named as DuCOM program. Following these models, the simulated results on the chlorides transport in several wetting-drying cycles are obtained. The adaptation of this model can be used to realize the quantitative effect of concerned parameters in macro level. Thus, DuCOM is a tool to obtain the result for analysis in this paper.

## 3.2 Steady-State Simulation

In order to understand how CL moves inside and outside along concrete depth, many cases of environment were set partially starting from steady state of environment and various wetting and drying period. Some parameters such as ambient RH and wetting and drying interval were studied by Swatekititham et al [14]. The concrete property is concrete with w/c of 0.55 under standard curing condition of submerged 28-days condition. The steady-state chloride concentration in the ambient relative humidity under constant of ambient chloride concentration at 3% NaCl is simulated. The results of 3 different RH of 30%, 70% and 99.9% show in **Fig.2.3.1-2.3.3**.

In low level of ambient RH, the RH distribution inside concrete at surface layer decreases to reach equilibrium of hydraulic pressure in pore solution to environment. However, in deeper position inside concrete, RH decreases gradually until all position is equilibrium. Within long-term analysis until 40 years, RH is same as ambient environment throughout the depth inside concrete.

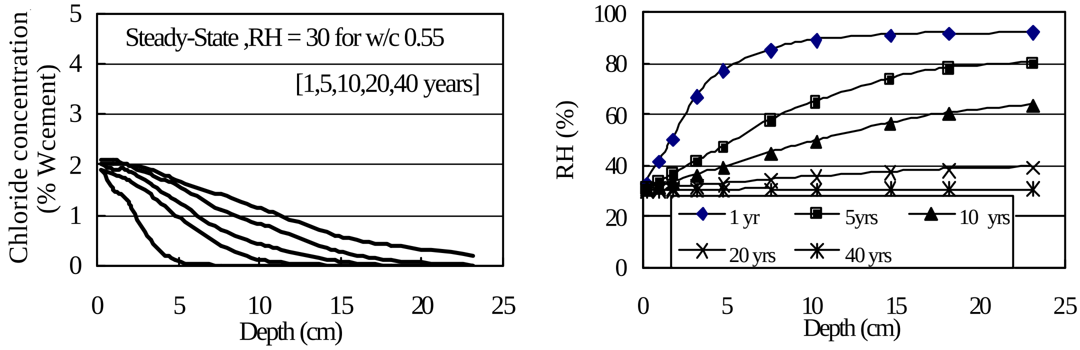



**Fig.3.2.1:** Chloride distribution (kg/m³) and relative humidity (%) profiles at 30% ambient RH

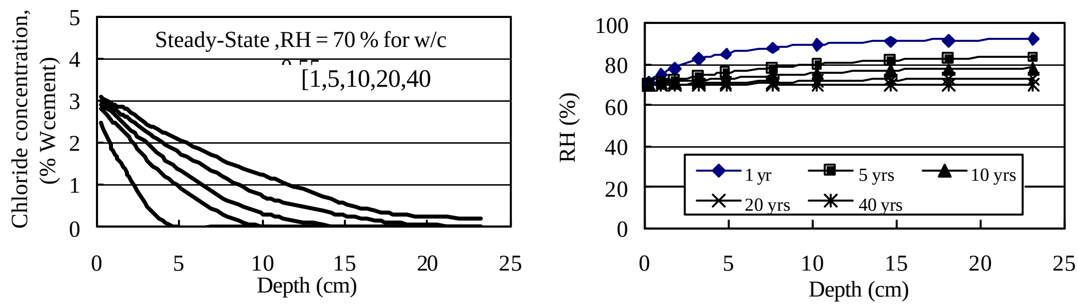



**Fig.3.2.2:** Chloride distribution (kg/m³) and relative humidity (%) profiles at 70% ambient RH,

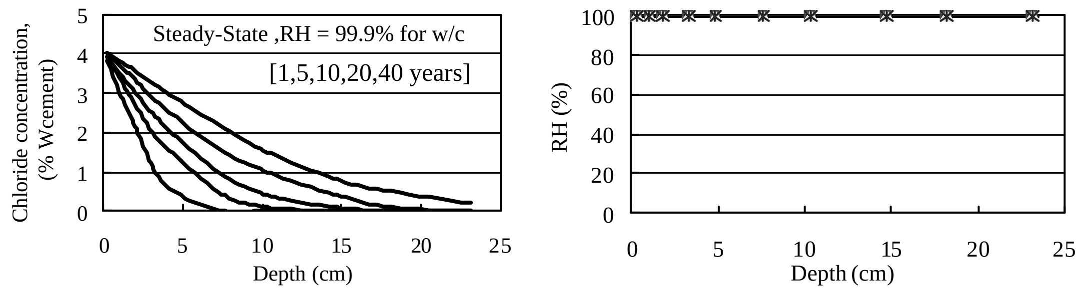



**Fig.3.2.3:** Chloride distribution (kg/m³) and relative humidity (%) profiles at 99.9% ambient RH,

## 3.3 Cyclic Wetting-Drying Simulation

The input data for replicating the mechanism is the concrete with water to cement ratio of 0.55 in 28-days standard curing in water with temperature of 20°c. The chloride ions concentration of environment is set equal to 0.51mol/l corresponding to 3% of salt concentration. The first input data in **Fig.3.3.1** is the consideration of long-term wetting: 3-days wetting and 10-days drying condition. The second set in **Fig.3.3.2** is short-term wetting: 1-day wetting and 10-days drying. In these 2 sets, the same conditions for wetting and drying states are given by; 30% RH is given for drying, whereas 99.9% RH is set for wetting. The third set in **Fig.3.3.3** is short-term iteration of 1-day wetting and 1-day drying. Moreover, the fourth set in **Fig.3.3.4** is the short-term wetting condition same as in the third set, nevertheless 60% RH is substituted for drying phase in order to compare RH effects.

The results are shown in 4 sets of figures in different wetting and drying conditions. The first figure is in steady state condition and the second to fourth figures are 3-days wetting and 10-days drying, 1-day wetting and 10-days drying (RH 30%) and 1-day wetting and 10-days drying (RH 60%), in sequence. All figures show the distributions of chloride ions concentration after having wetting-drying cycles with RH distribution. **Fig. 3.3.1** shows 2 results under different ambient RH: 30% and 99.9%. In fact, high RH condition accelerates diffusive movement of chloride ions. Thus, the concentration at surface would be considered as a function of ambient RH. The maximum concentration in concrete is about 2% by weight of cement in case of 30% RH and 4% in case of 99.9% RH.

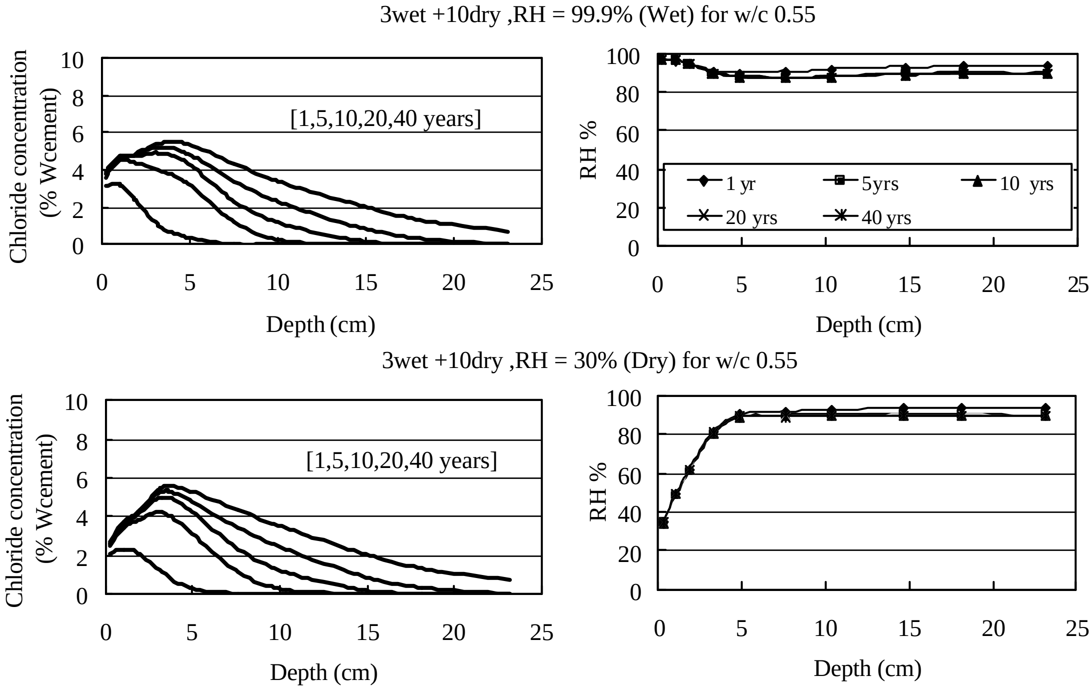



**Fig. 3.3.1:** Chloride distribution (% Wcement) in the cyclic wetting-drying condition of 3-10 case [Drying RH = 30% and Wetting RH = 99.9%]

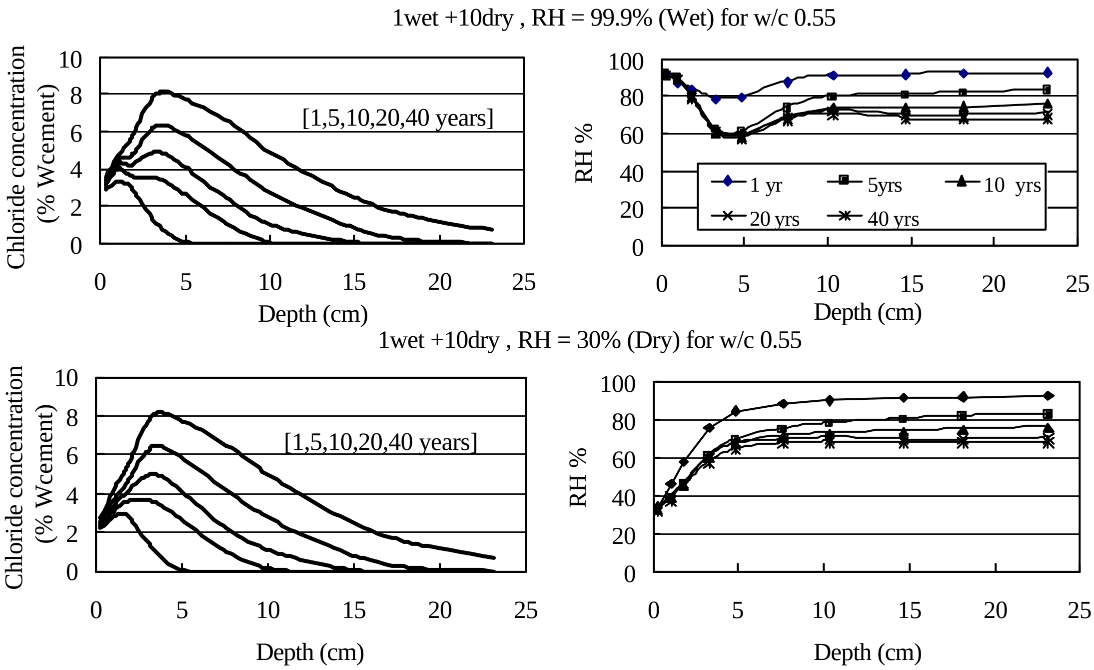



**Fig.3.3.2:** Chloride distribution (% Wcement) in the cyclic wetting-drying condition of 1-10 case [Drying RH = 30% and Wetting RH = 99.9%]

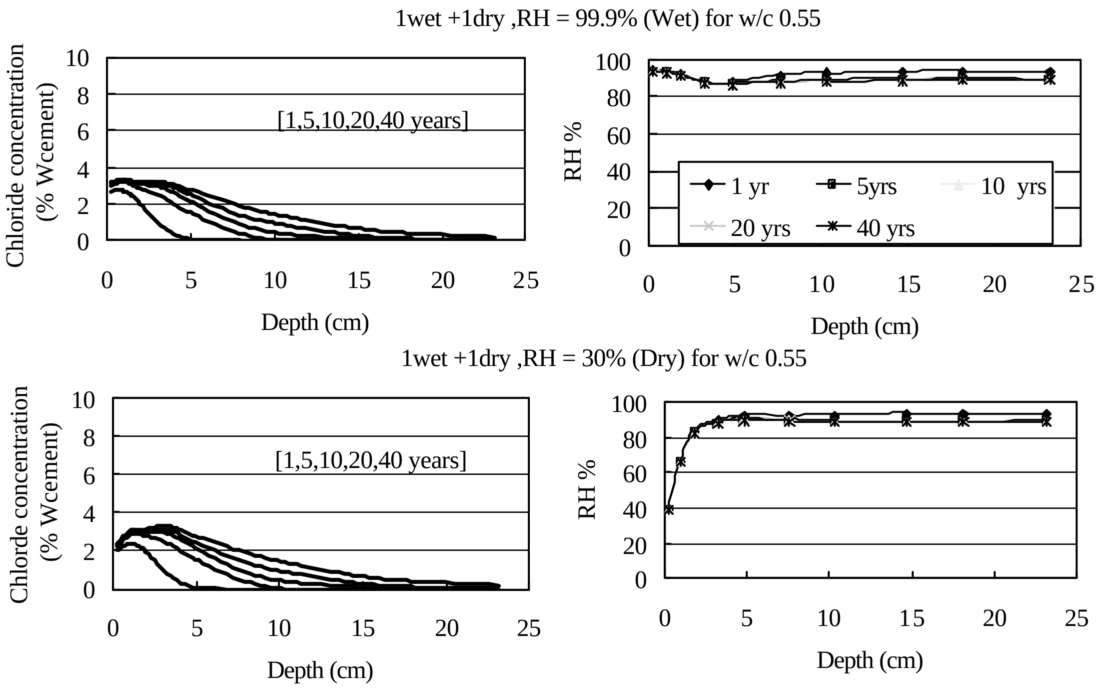



**Fig.3.3.3:** Chloride distribution (% Wcement) in the cyclic wetting-drying condition of 1-1 case [Drying RH = 30% and Wetting RH = 99.9%]

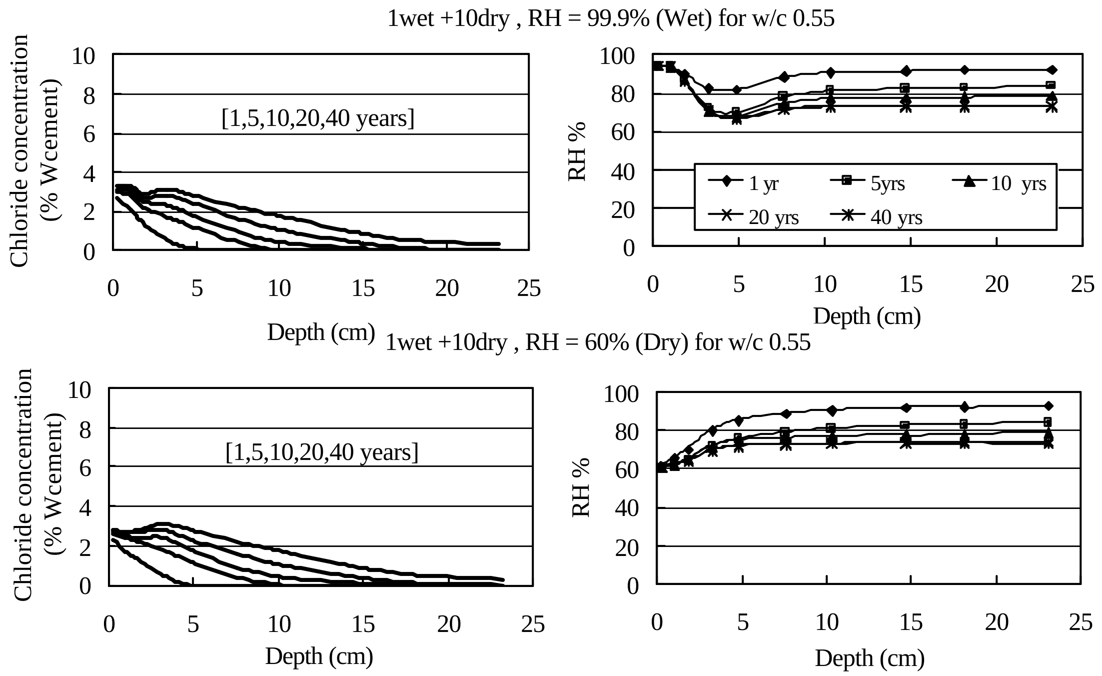



**Fig.3.3.4:** Chloride distribution (% Wcement) in the cyclic wetting-drying condition of 1-10 case [Drying RH = 60% and Wetting RH = 99.9%]

By this result, the steady state of RH condition, the chlorides concentration has a peak at the surface of concrete. Next, **Fig. 3.3.2** is set as long-term wetting of 3-days wetting and 10-days drying. The wetting period is set as 99.9% RH and the drying period is set as 30% RH. As a results, the RH gradient from wet-to-dry relates with condensation and advection force in pore solution in an exponential function.

Looking at the RH distribution, the RH increases up to 99.9% during the wetting and decreases to 30% during the drying. In a cycle of wetting and drying, RH is nearly constant throughout the depth after 5cm because of very low rate of moisture transfer forward and backward. The combination of high gradient of RH near surface and a constant RH after 5cm results in the non-recovered of RH at the depth of 3.5-5 cm. That leads us to understand that wetting cannot increase RH all over the depth to be the level of 99.9% at last of wetting time. However, the case of long-term wetting can prevent dropping of RH at later 5cm depth and keep constant with time. Compared with the case in **Fig. 3.3.3** of short-term wetting, that is 1-day wetting and 10-days drying condition, the wetting period is too short in order to prevent the decreasing of RH inside as in the long-term wetting. The large gradient in terms of RH distribution, especially at 3-5 cm, causes large water suction, which accelerates chloride migration into concrete. The analytical results show that the peak of chloride concentration exists at the position of lowest RH. During the wetting period, RH from surface and inside will be transferred to the depth of 3.5 cm and bringing chloride ions to accumulate in this position. In opposite, the peak of chloride ions is decreased by diffusing and moisture movement outward from concrete during drying. Comparing influences in wetting with those in drying, the effect during the wetting has higher impact than that during drying. The parameters influencing on the chloride content at peak position are the wetting period and the ambient RH. According with the samples of several wetting-drying cycles, 1-10 case in **Fig 3.3.2** is the most severe in condensation at the peak position inside concrete. The gradient of RH in dry-to-wet state is large as 30% to 99.9%. However the gradient of RH is reduced to 60% to 99.9% range, how much it influences to the condensation inside concrete. The peak position had been thought that the chloride concentration is not as severe as in case of large gradient of RH. This phenomenon is expressed in **Fig. 3.3.4** of short-term wetting with 60% RH during drying. Its RH distribution is not dramatically different, as the result the chloride content at peak position is not shown as high as previous case. As mention above, the peak chloride concentration in concrete increases exponential when the gradient of wet-to-dry RH is large.

## 3.4 Actual Cyclic Wetting and Drying Simulation

The simulation in this section is done in the objective of analyzing actual environmental effects for structures in the atmosphere. The environmental conditions in Kochi Prefecture are used to simulate the chloride transport. The change of the weather is not as severe as the uniform wetting-drying cycles due to the gradually change in temperature and relative humidity. Therefore the relative humidity in a year is scattered due to the change of the seasons. The chlorides transport in the winter season and the rainy season are totally different. During a month in each season, the amount of raining day is different, thus the wetting period to drying period ratio makes the chloride transport in different amount and results to different of the total chloride concentration. The environmental conditions are investigated in every hour. The study was separated into three particular environmental conditions of

**Case 1)** 10-years iteration of monthly weather in the winter of (Feb 2003); the 25-93% of ambient relative humidity and 5-10% of raining period are expressed as the environmental conditions.

**Case 2)** 10-years iteration of monthly weather in the rainy season of (Jul, 2003); the 45-93% of ambient relative humidity and 15-20% of raining period are expressed as the environmental conditions

**Case 3)** 10-years iteration of the weather in one-year period (Sep 2002 to Aug 2003); the 25-93% of ambient relative humidity and 10% average of raining period are expressed as the environmental conditions.

The scattering of the ambient relative humidity in the atmosphere does not effect on the chloride transport as severe as the uniform wetting-drying cycles described as in **Section 3.3**. The scattering of the environmental conditions of Kochi in Feb and Jul are shown in **Fig.3.4.1** and **Fig.3.4.2.**

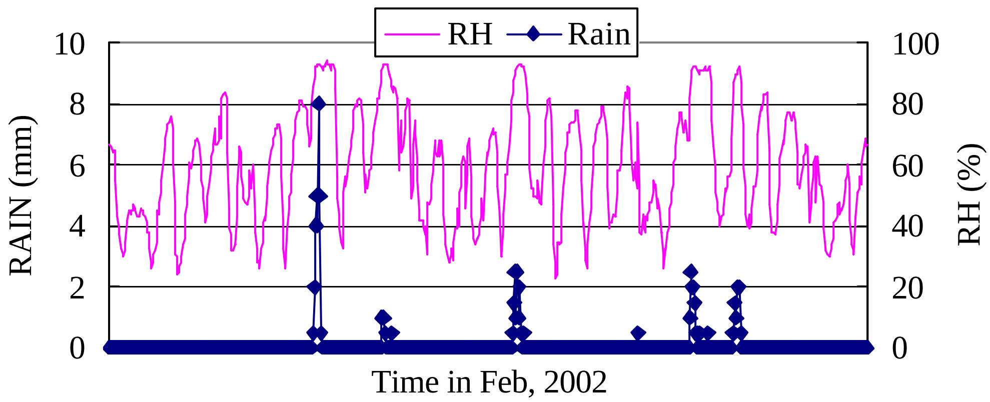



**Fig.3.4.1:** Ambient Rain and RH in Kochi prefecture, February 2002

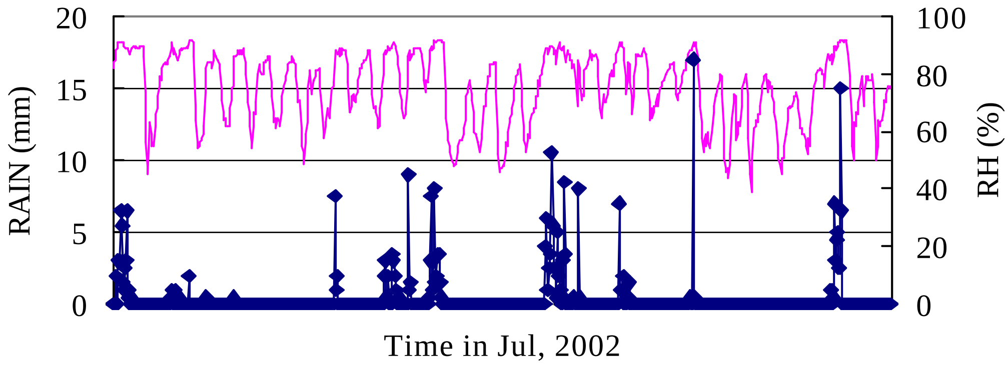



**Fig.3.4.2:** Ambient Rain and RH in Kochi prefecture, July 2002

The actual environment is modified during raining by assuming ambient RH is 99.9% due to surface saturation. It is noted that RH of 99.9% represents wet condition instead of 100% due to the capable of equilibrium achievement. The characteristic of weather condition in Feb has low raining and high scattering of RH. Contrasting with, the weather in Jul has high raining and low scattering of RH.

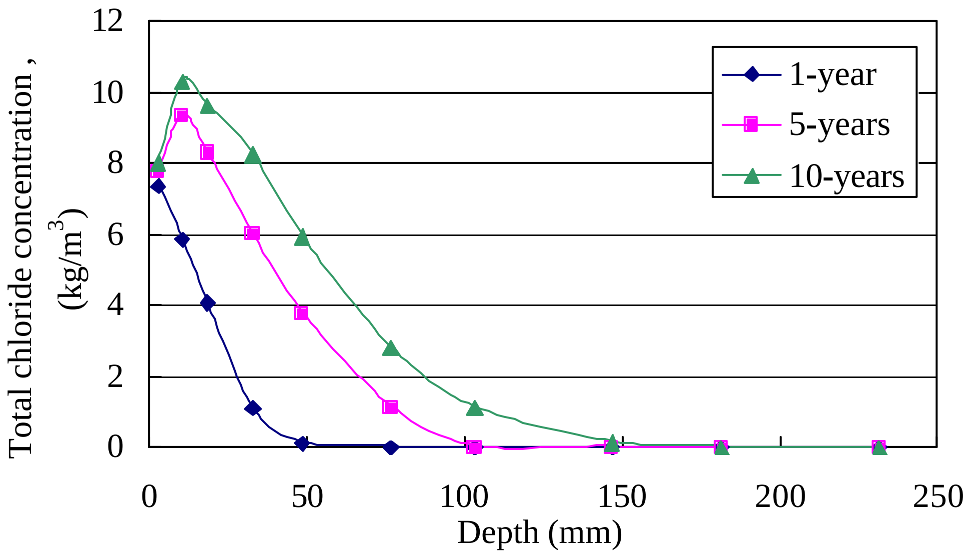



**Fig.3.4.3:** Chloride distribution in case 1 calculated by DuCOM

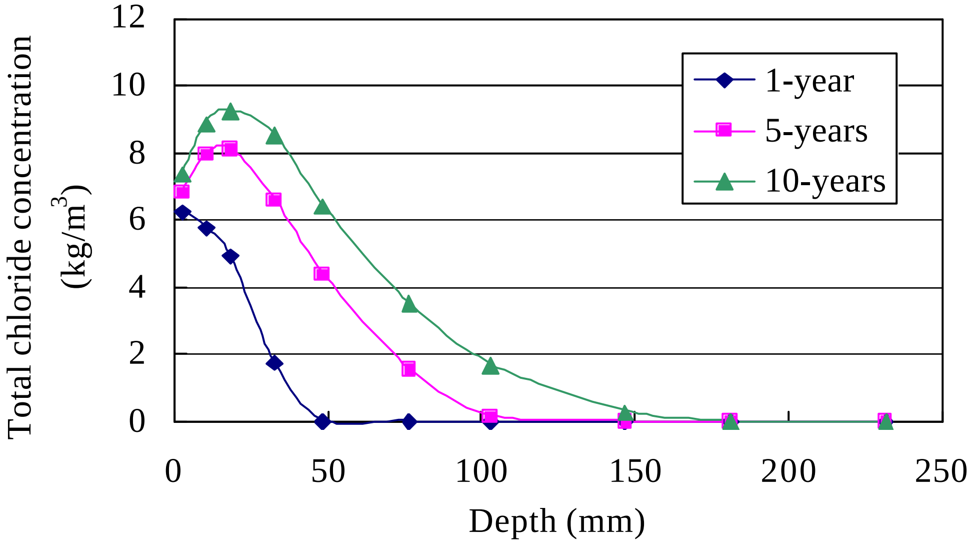



**Fig.3.4.4:** Chloride distribution in case 1 calculated by DuCOM

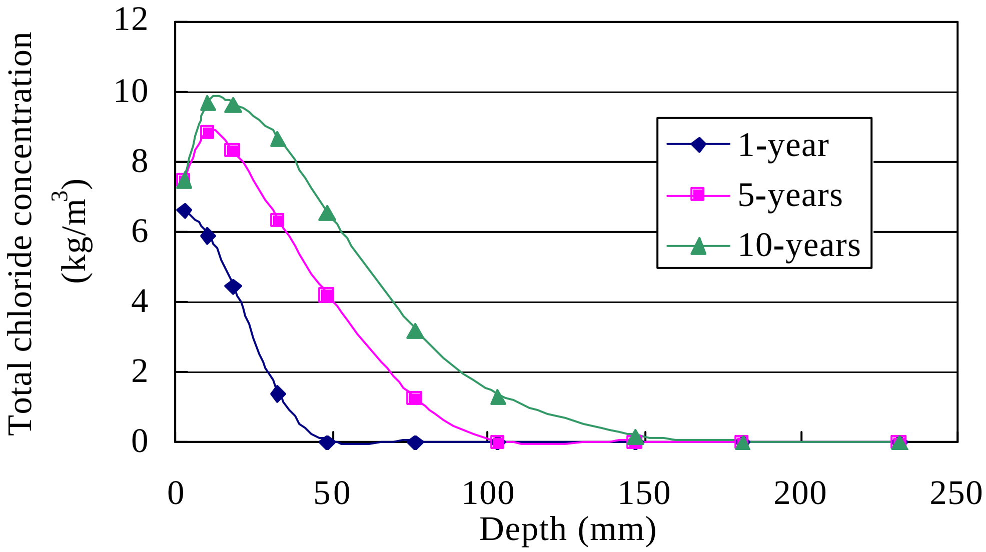



**Fig.3.4.5:** Chloride distribution in case 1 calculated by DuCOM

The ambient chloride concentration is fixed constant at 0.51mol/l. The concrete of water to cement ratio of 0.55 with 28-days water curing is applied. The simulation results of the three cases are shown in **Fig.3.4.3** to **Fig.3.4.5**, respectively. The results differ among them in very few amounts of the total chloride distribution even the ambient relative humidity changes much. The scattering of the ambient relative humidity in the atmosphere does not effect on the chloride transport as severe as the uniform wetting-drying cycles. The actual environments change gradually and lead the consequence of low advection in concrete similar to the uniform wetting-drying cycles.

## 3.5 Summary

The study of macro analysis of environmental effect of ambient relative humidity and cyclic wetting-drying condition tells us what the main parameter on chloride transport is. The results from this study are in steady and non steady states. The wetting-drying cycles are used to compare with the actual investigated data existing at this moment. Therefore, the actual environment cannot explain the different of severity in various locations around Japan. Next, the simulation of chloride transport for the structures in the atmosphere has mainly parameters on the available airborne chlorides and how they transport to concrete. Flow chart in **Fig.1.2** shows the dimension of this research work and environmental condition has the effect on the surface chloride accumulation more than its on chloride transportation in concrete. Thus scope of this research work is set as the study of the airborne formation, transportation and accumulation at the surface of concrete structures. Others environmental factors, such as wind and seashore scenery become the parametric study.

# CHAPTER 4

# Mechanisms of airborne chloride formation and transport

## 4.1 General

Recently, some coastal areas are being utilized as residential areas. However, various salt damages of the structures in coastal areas are well known experimentally. The basic mechanism of salt damage has been clarified depending on the concentration of chloride ions available in the atmosphere, humidity and temperature.

In thinking of countermeasures for salt damage, it is important to know how sea salt is formed, transported in the atmosphere and adsorbed on the structural surface. The prediction of airborne chlorides volume and sizes distribution at the coastal areas is dependent on the condition of the weather and location.

The airborne chloride is formed by the sea wave breaking produces spray droplets, which is estimated as the second power of the wind speed. In high wind speed, spray droplets rapidly increases the effective surface area of the ocean and therefore, should enhance the exchange of any constituent or property normally transferred across the air-sea interface. In addition, wind causes the driven force to form a certain wave height. Thus energy form wave in the relationship with wave height was proposed [35-36].

Sea spray plays a role in the marine boundary layer as well. Spray dehydrates into sea-salt aerosol (a major component of marine aerosol) and, thus contributes to climate forcing either directly by sunlight [15]. Relative to bulk seawater, the bubbles from which most spray droplets and sea-salt aerosols originate are also concentrated in marine surfactants and, consequently, enhance the air-sea fluxes of particular organic matter. Moreover, breaking seawater by hitting a breaking wall and wave-blocked concrete is thought as a main criterion of the formation. The magnitude of the spray effect as a function of wind speed, however, is a subject of heated debate. Likewise, Makin 1998 concluded from his modeling that ‘for wind speeds below 18 m/s, there is no drastic impact of spray on heat and moisture flux. However, it is considered as a minor factor that is ignored in the analysis in this paper. The formation and transportation of airborne chlorides is summarized as

- Wave breaking and airborne chlorides formation
- Particle size and weight distribution
- Gravitational falling out
- Adsorption & absorption on surface of building structures

The formation of aerosol particles at seashore in the atmosphere has distribution in the large size of available airborne particles in the air [18]. The airborne particle sizes are from 2 μm to more than 100 μm in the range of coarse particle distribution. Most of the particles in the coarse mode are formed by the frictional processes of comminuting, such as sea spray from breaking waves and the slow growth of particles from the accumulation mode. Typically, the airborne particles of a few tens to hundreds per $cm^3$ are in the coarse mode in an urban area. The transport process depends on the mechanisms of meteorological conditions of wind velocity, wind direction, turbulence by wind atmospheric stability. The transportation of each particle differs in distance due to the gravitation falling out. The speed of falling out and time consuming before touching the ground surface is able to use for simulation as the time which windblown can carry the particles to further distance. The anonymous of airborne chlorides formation by wave breaking at seashore leads the problem as unknown boundary conditions. There are some of the methodologies for measuring airborne particles [33, 34], but it is not a simple device and also expensive. The apparatus can measure the volumetric value, but it seems really impossible to obtain particle size distribution. Even the apparatus is able to measure; the guarantee of accuracy is not approved. Thus the simplification on the model of airborne chloride transport is modeled under the related parameters which discuss later.

## 4.2 Model on airborne chlorides formation

The mechanism of airborne particles formation is due to sea wave, sea slope, and offshore topography. The amount of airborne particles flying to the atmosphere is considered as in the function of wind speed and wave height. However, the factor causing wave in a certain height depends on the wind speed and movement of sea base. The model explains the mechanism of airborne particle formation in an assumption of wave breaking by concrete obstacle along shoreline. After breaking, the overall particles fly to a certain height. In fact, the particle size distribution along the height is necessary for the transportation in the atmosphere. In this study, the entire particles are flown upward to the same height. This equivalent height is called as the initial flying height.

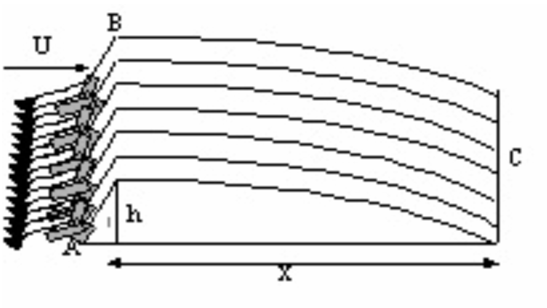



**Fig. 4.2.1:** The simple figure of airborne chloride transport

In **Fig.4.2.1**, the wind speed at sea surface acts as driven force to the wave to concrete water breakings. Simultaneously, the upper wind acts as the driven force to the airborne chlorides transport along the distance from seashore. Thus, the energy from the wind transfers to the airborne particles and allow the particles to move with the speed of U, horizontally. Again, the wind speed data using in this analysis is used the average wind speed in hourly constantly with distance from seashore and height from mean sea level, as well.

Applying the energy theorem, the height of particles movement at point A to point B in **Fig 4.2.1** is related with wind speed in the second power. In addition, sea wave in a certain height gives extra energy for driving airborne particles moving in higher distance. The energy from wave [35] is proportional to the wave height and wind speed as shown

$$E = \frac{1}{8} r_{sea} \, g h_{wave}^{2} \tag{4.2.1}$$

where, $\rho_{sea}$ is the density of seawater (kg/m$^3$)

$h_{wave}$ is height of wave (m/s) (= proportional to wind speed, U)

g is gravitational acceleration (m/s$^2$)

h is the initial flying height (m)

U is the wind speed (m/s)

The calculation of the initial height is simplified depending on the function of wind speed only. The initial flying height (h) at B point is calculated by

$$h = b .a .U^{2} \qquad (4.2.2)$$

where, β is the modification factor due to wave energy (= 4/3)

α is the modification factor due to wind speed (= 1/2g)

Despite the fact that, wave energy in the equation is containing in the wave before breaking by concrete blocks. Hence, some of energy is absorbed by the concrete wave breaking, and the residual energy still stored within the airborne particles. The energy of the airborne particles driving upward is the combination between kinetic energy and residual energy inside the airborne droplets. At this moment, the amount of absorbed energy after wave breaking giving to the airborne particles is unknown. Therefore, the airborne particles movement in upward direction is due to the combination of both wind and wave energy. In fact, the wave energy due to wave height is also related with wind speed, the speed of upward movement should be in the function of wind, as well. In fact of the combination between kinetic energy and the residual energy from wave, the initial flying height is higher than that in the case of neglecting wave energy. According to this unknown of residual energy from breaking wave, the simplification on the equivalent of flying height should be done for more precise calculation. Value of h calculated by **Eq.4.2.2** is the empirical formula estimating the actual flying height of the airborne particles. The multiplication factors are proposed in this study as β and α. The value of α is considered as the coefficient expressing the relationship between the initial flying height and the wind speed. In this paper, the value of α is recommended as equal to 1/2g. Furthermore, the value of β is expressed as the multiplication factor due to the additional of residual energy from wave. The consideration of sea slope and shape of the obstacles along shoreline is neglected. Thus, the average residual energy of wave after breaking is thought as 4/3 of the initial flying height due to the driving energy of wind speed. Thus, the computation of airborne particles formation flying to a certain height is averaged for the verification of data allover Japan. The relationship between the initial flying height and the wind speed is computed as shown in **Fig.4.2.2**.

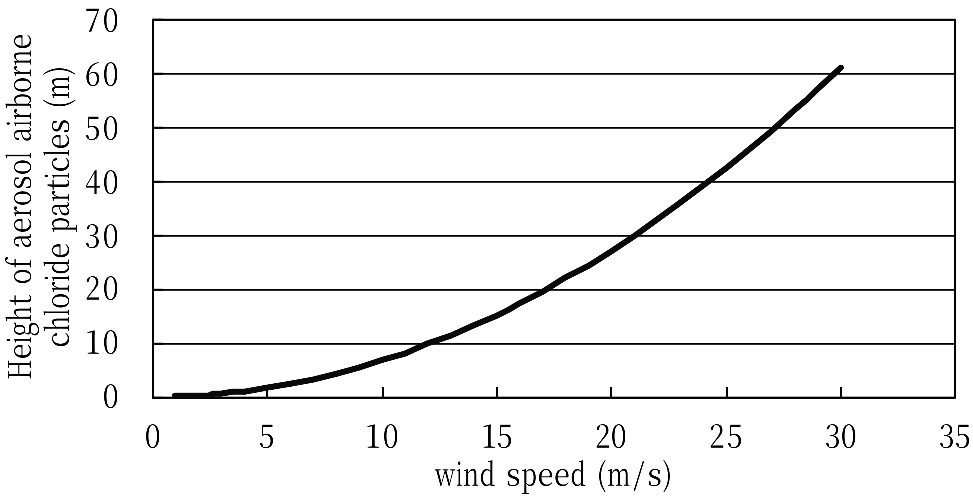



**Fig. 4.2.2:** Relation of height of aerosol and wind speed in **Eq.4.2.2**

## 4.3 Model on airborne chlorides transportation

Next the transportation from an initial flying height through the distance is considered by the law of motion of a particle in the air. At the same time the gravitational force makes the particle fall down to the ground. This phenomenon is called as gravitational settlement. The rate at which a particle falls through air under the action of gravity depends not only upon the size and density of the particle but also its shape. The majority of analyses in this subject assume that each particle is the spherical shape.

In general, the mechanism of transportation is due to gravitational settlement. However, the complicate simulation of the particles movement needs the computational program. Moreover, the actual scenery at seashore such as, residents, tree, and etc., has a difficulty of the particles transport. The computational model should be proposed in an average free-space movement without obstacle along the moving path. The mechanisms are the advection due to winds and the gravitational settlement as criteria for simulating the transportation.

When a body is suspended in airflow, 3 components of forces are acting on the airborne particle. One is the self-weight of the body within prevailing gravitational field. The weight of sphere of diameter d is

$$W = 1/6.\rho_s.\pi.d^3.g \qquad (4.3.1)$$

Second is the resisting force due to the volumetric up trust force. During gravity, the sphere displaces it own volume of fluid and will experience the up trust force equal to the weight of fluid displaced, i.e.

$$N_{uptrust} = 1/6.\rho_{air}.\pi.d^3.g \qquad (4.3.2)$$

where, .$\rho_s$ is density of particles (kg/m$^3$) = 1086 kg/m$^3$

.$\rho_a$ is density of air (kg/m$^3$) = 1.29 kg/m$^3$ at 1 atm [29]

d is particle diameter (m)

Thirdly is the drag force on resisting on the projected area of spherical shape of airborne particle. The particle is moving relative to airflow then it will experience a further resistance due to drag. A general expression of drag force is

$$N_{drag} = 1/2\ C_d\ A_b.\rho_{air}\ v^2 \qquad (4.3.3)$$

where, $C_d$ is coefficient of drag

$A_b$ is projected area ($\pi d^2/4$), $m^2$

v is constant dropping speed (m/s)

Many investigators have investigated relationships between drag coefficient, $C_d$, and Reynolds' Number, Re, for fully submerged bodies. For the particular case of laminar flow around a particle, Sir George G. Stokes (1819-1903) proposed that

$$C_d = 24 / Re \qquad (4.3.4)$$

And

$$Re = \rho_{air}.v.d / \mu_{air} \qquad (4.3.5)$$

where, $\mu_a$ is dynamic viscosity of air ($Ns/m^2$)

Substitution of Eq. (4.3.4-4.3.5) to Eq. (4.3.3) gets

$$N_{drag} = 3\pi v.\mu_{air}.d \qquad (4.3.6)$$

The equilibrium of the vertical motion due to the balancing of force acting at the airborne particle is shown in **Fig. 4.3.1**. Therefore the up trust or uplift force resisting the particle is much smaller than the gravitational force according to the density of air medium is only 1.29 kg/m$^3$ in 1 STP. The particle accelerates downwards, its velocity, v, and increases until the drag equals the downward force. As described above, the equilibrium of gravitational motion is written as

$$\frac{1}{6}pd^3 g(r_s - r_{air}) = 3pvm_{air}d \qquad (4.3.7)$$

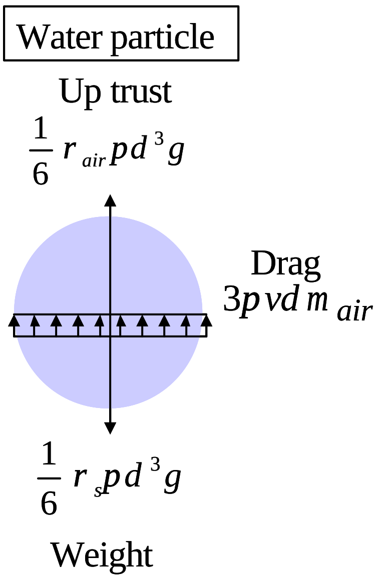



**Fig. 4.3.1:** Equilibrium of vertical force by gravitational settlement.

The equation is referred as Stokes' Law, where up trust force is negligible ($\rho_s >> \rho_{air}$). The value of $\mu_{air}$ is calculated by kinematic viscosity divided by density of air. The kinematic viscosity of air at 1atm shows the function of temperature as in **Fig. 4.3.2**.

Referred to **Fig. 4.3.3**, the vertical motion by gravitational force at the maximum height falls down with gravity acceleration (m/s$^2$). The decreasing of acceleration occurs from the drag resistance. At a certain height, h, the vertical acceleration is zero and vertical movement is in constant wind speed.

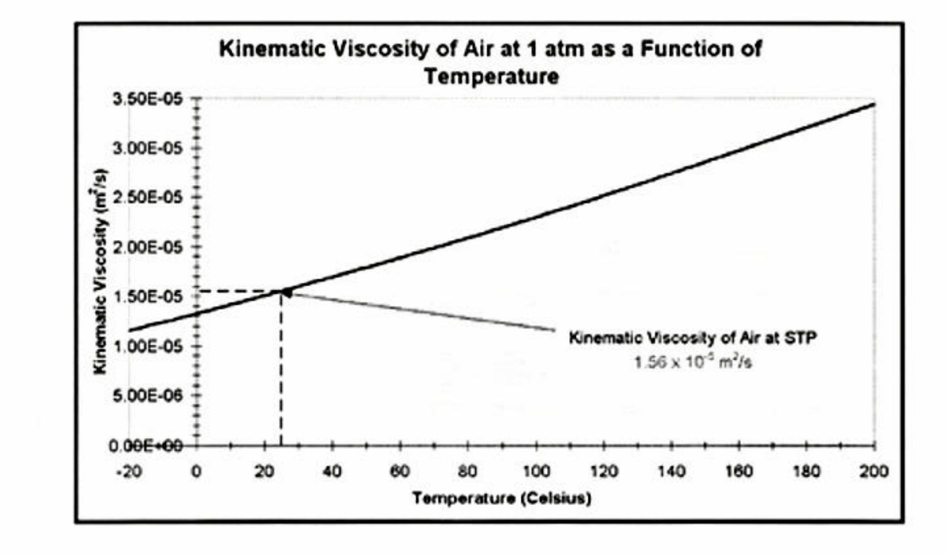



**Fig. 4.3.2:** Kinematic viscosity (m²/s) of air at 1atm as a function of temperature (°c) obtained from (www.ce.utexas.edu)

During vertical motion, horizontal wind speed brings the particle transport for a distance. Wind speed and particle size affect to how long it can be blown. Thus, total time of transportation t is computable as the equilibrium of motion in both vertical and horizontal direction.

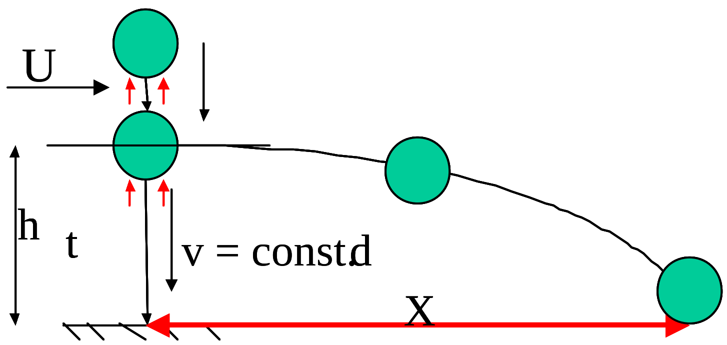



**Fig. 4.3.3:** Transport mechanism due to vertical and horizontal motion.

$$t = h/v = X/U \qquad (4.3.8)$$

where, X is the horizontal distance (m)

t is the transportation time to the ground (sec)

v, is vertical speed (m/s)

The **Eq.4.3.7** integrates with **Eq.4.3.8** and the result shows the relationship between vertical speed and the specific particle size as illustrated in **Fig.4.3.4**.

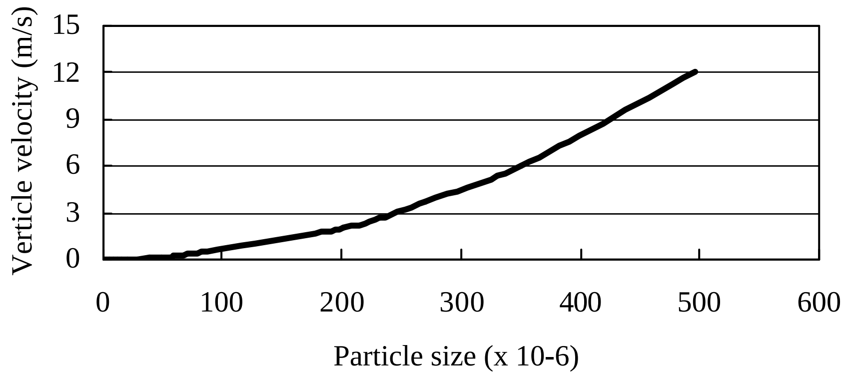



**Fig. 4.3.4:** Relationship between dropping velocity and specific particle sizes

At a constant wind speed, a water particle size is dropped at a distance depending on size. In this behavior, it becomes the important of this model on the hypothesis that a structural location, only 1-size of airborne chlorides can fly to it. This assumption is under the condition of constant wind speed. Conversely, the actual environment has fluctuation of wind speed in a period of time, thus in this study, the consideration of wind speed is necessary in the hourly interval. This is a laborious work on simulating chloride concentration at surface of concrete accumulated a numbers of years, but the simulation in every hours is done for high accuracy. As a result, wind fluctuation during an hour is averaged as a constant value. This constant wind speed is used to analyze the particle size that can fly to a considered structure. As shown in **Fig.4.3.5**, one effective size can fly to a specific distance as followed the Newton's Law.

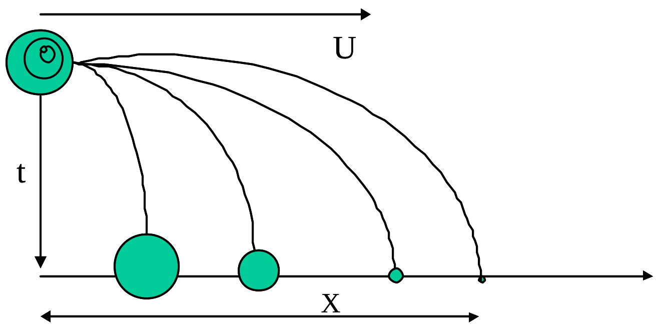



**Fig. 4.3.5:** Profile of 1-size particle affects on a distance in a constant wind speed U

The results of wind speed and particle size relationship with the distance from seashore are shown in **Fig. 4.3.6**. Next the volume of each particle size is unknown; consequently the investigation of particle size distribution and volume is necessary. Although, there is no means to observe the volume and size distribution at seashore area, the indirect method is proposed in this model. The method is done in backward from the investigated data by PWRI [1] combining with above discussion. Thus, the particle size distribution and volume of salt is assumed for reaching the investigated results. In addition, the wind speed influences the volume and size distribution as well. This phenomenon happens because winds result strong wave and large volume of aerosol. The reference of volumetric water particle at seashore is set as 2.0mm$^3$/dm$^2$/hr with wind relationship at 2m/s. Inside the water particle, it contains 3% of salt concentration as same as the concentration form sea. The value of 0.06mg/dm$^2$/hr is the calculation of weight of chlorides content in the water particle. The particle distribution the reference wind speed is calculated by the assumption of normal distribution with the standard deviation, $\sigma$, of 18 $\mu$m. The conversion from volume of airborne water particles flying to a structure is done to obtain the weight of chlorides content (mg). In the **Fig. 4.3.7**, the x-axis is the particle size, which relates to the distance from seashore. At the peak value of chloride content by weight, it is equivalent to the distance at seashore (= about 10m length from concrete wave breaking to average coastline). The smaller particle sizes can transport in further distance from seashore. The particle size at 33µm is the particle size dropping at seashore, and the particle sizes in right-half of the normal distribution do not take into account. Since, the large size particles drops at very short distance within 10m from the concrete wave breaking.

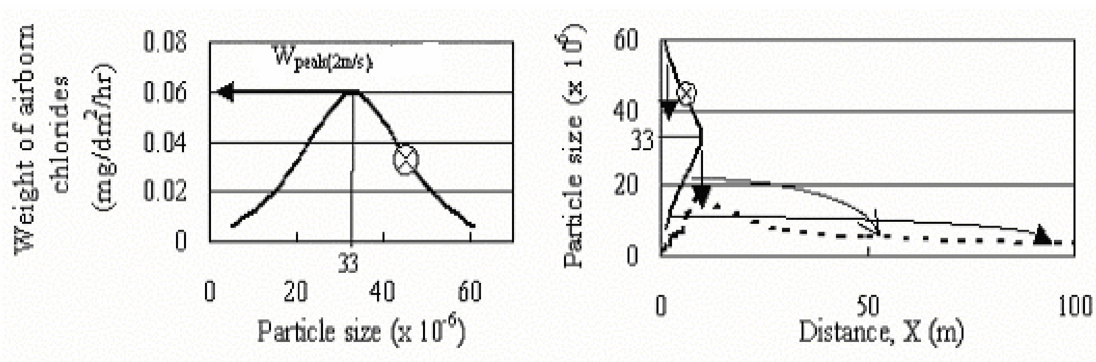



**Fig. 4.3.7:** The reference value of chloride content with particle size (µm) under the condition of 2 m/s wind speed and standard deviation at 18 (µm)

The normal distributions of weight of airborne chloride in other wind speeds are calculated by the relationship of third power on reference wind speed. The weight of water particle at seashore in higher wind speed cause the larger volume of aerosol and bigger size distribution. The standard deviation of the size distribution is also considered as the max size ratio. The max size ratio means the proportion between maximum size at a wind speed (particle size at seashore) and reference wind sped (2m/s). The formula of modification for weight of chloride content is shown below

$$W_{peak,i} = W_{peak(2m/s)} \times [\frac{U}{2}]^3 \quad (4.3.9)$$

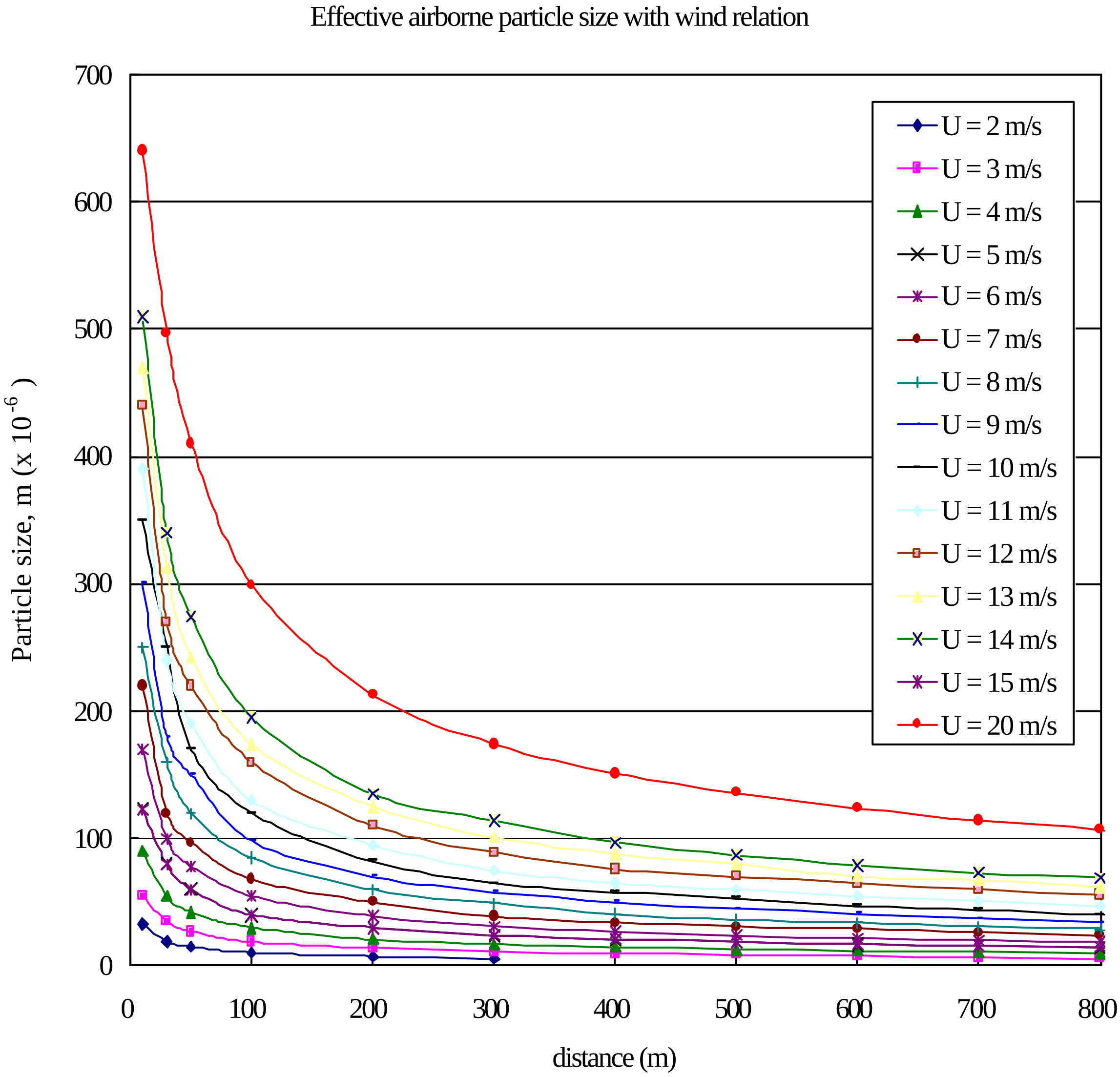



**Fig. 4.3.6:** The airborne particle size (μm) influence at a specific distance (m) in various wind speeds (m/s)

The formulation of modification for the standard deviation is shown as

$$s_i = s_{(2m/s)} \times \frac{d_{i,\max}}{d_{2,\max}} \qquad (4.3.10)$$

where, $d_{i,max}$ is maximum airborne particle size at seashore at a particular U

$d_{2,max}$ is maximum airborne particle size at seashore at U = 2m/s

$W_{peak}$ is the peak weight of airborne chloride at U ($mg/dm^2/hr$)

$W_{peak(2m/s)}$ is the peak weight of airborne chloride at U=2 m/s ($mg/dm^2/hr$)

$\sigma_i$ is standard deviation at U ((μm)

$\sigma_{(2m/s)}$ is standard deviation at U = 2 m/s (μm)

The interrelation among wind speed, distance and chlorides content are known as shown in **Table 4.3.1**. Then, wind directions are important parameters, the consideration of wind directions should be linked with the formula described above. In each location, the effective wind speed is defined as the shortest distance from sea to the considered distance. For example, the investigation of a structure in Kochi prefecture is due to South wind. Other wind directions in ± 67.5° from south generally influence to flying of airborne chloride to the structure. It is noted that the wind direction may not be always fixed at ± 67.5°, due to the panorama of coastline. However the effect of wind direct is considered by equivalent to the distance from seashore. For example, a structure locates at X (m) from seashore with the efficient wind direction from South. Once wind direction changed to S-W direction, the distance that airborne chlorides fly to the structure is longer. The distance in an efficient wind speed (X') is calculated by

$$X' = X / \cos\varphi \qquad (4.3.11)$$

where, $\varphi$ is angle of an efficient wind to effective wind direction [Ex. S-W is 45°]

**Table 4.3.1:** Value of airborne particle size and chloride content related with wind and distance from seashore calculated from reference value in **Fig. 4.3.7** with **Eq.(4.3.9-4.3.10**)

| | | Airborne Particle Size (m x$10^{-6}$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U / Dist (m) | | **10** | **30** | **50** | **100** | **200** | **300** | **400** | **500** | **600** | **700** | **800** |
| **1** | | 12 | 7 | 6 | 4 | 3 | 2 | 0 | 0 | 0 | 0 | 0 |
| **2** | | 33 | 19 | 15 | 10.5 | 7.4 | 5.9 | 5 | 4 | 3 | 0 | 0 |
| **3** | | 55 | 35 | 27 | 19 | 14 | 11 | 9.5 | 9 | 8 | 7 | 6 |
| **4** | | 90 | 55 | 42 | 30 | 21 | 17 | 15 | 13 | 12 | 11 | 10 |
| **5** | | 123 | 80 | 60 | 40 | 30 | 24 | 21 | 19 | 17 | 16 | 15 |
| **6** | | 170 | 100 | 78 | 55 | 39 | 31 | 27 | 24 | 22 | 20 | 19 |
| **7** | | 220 | 120 | 97 | 68 | 50 | 39 | 34 | 31 | 29 | 26 | 24 |
| **8** | | 250 | 160 | 120 | 85 | 60 | 49 | 41 | 36 | 34 | 31 | 29 |
| **9** | | 300 | 180 | 150 | 98 | 70 | 58 | 50 | 45 | 41 | 37 | 34 |
| **10** | | 350 | 250 | 170 | 120 | 82 | 65 | 58 | 53 | 47 | 44 | 40 |
| **11** | | 390 | 240 | 190 | 130 | 95 | 75 | 65 | 60 | 55 | 51 | 47 |
| **12** | | 440 | 270 | 220 | 160 | 110 | 89 | 76 | 70 | 65 | 60 | 56 |
| **13** | | 470 | 313 | 242 | 174 | 125 | 101 | 88 | 80 | 70 | 67 | 62 |
| **14** | | 510 | 340 | 274 | 195 | 135 | 114 | 97 | 87 | 79 | 73 | 69 |
| **15** | | 545 | 378 | 300 | 214 | 154 | 125 | 109 | 96 | 88 | 82 | 76 |
| **20** | | 640 | 497 | 410 | 299 | 213 | 174 | 151 | 136 | 124 | 114 | 107 |
| **25** | | 830 | 690 | 595 | 452 | 326 | 267 | 232 | 207 | 190 | 176 | 165 |
| **30** | | 934 | 820 | 728 | 579 | 426 | 350 | 305 | 270 | 248 | 230 | 220 |

| U= | SD | Weight of chloride content (mg/$dm^2$/hr) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **6.5** | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **2** | **18.0** | 0.06 | 0.03 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 |
| **3** | **30.0** | 0.20 | 0.10 | 0.07 | 0.05 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.02 | 0.02 |
| **4** | **49.1** | 0.48 | 0.22 | 0.16 | 0.11 | 0.08 | 0.07 | 0.06 | 0.06 | 0.05 | 0.05 | 0.05 |
| **5** | **67.1** | 0.94 | 0.50 | 0.33 | 0.20 | 0.16 | 0.13 | 0.12 | 0.11 | 0.11 | 0.10 | 0.10 |
| **6** | **92.7** | 1.62 | 0.70 | 0.52 | 0.35 | 0.26 | 0.22 | 0.20 | 0.19 | 0.18 | 0.17 | 0.17 |
| **7** | **120.0** | 2.40 | 0.84 | 0.73 | 0.49 | 0.38 | 0.32 | 0.29 | 0.28 | 0.27 | 0.25 | 0.25 |
| **8** | **136.4** | 3.84 | 1.97 | 1.31 | 0.87 | 0.63 | 0.54 | 0.48 | 0.45 | 0.43 | 0.42 | 0.40 |
| **9** | **163.6** | 5.47 | 2.34 | 1.96 | 1.19 | 0.87 | 0.76 | 0.69 | 0.65 | 0.62 | 0.59 | 0.57 |
| **10** | **190.9** | 7.50 | 5.27 | 2.59 | 1.71 | 1.20 | 1.02 | 0.95 | 0.90 | 0.84 | 0.82 | 0.78 |
| **11** | **212.7** | 9.98 | 5.50 | 3.47 | 2.21 | 1.65 | 1.38 | 1.26 | 1.21 | 1.15 | 1.11 | 1.07 |
| **12** | **240.0** | 12.96 | 6.20 | 4.66 | 3.15 | 2.19 | 1.86 | 1.68 | 1.60 | 1.53 | 1.47 | 1.42 |
| **13** | **256.4** | 16.48 | 8.90 | 6.16 | 4.09 | 2.94 | 2.47 | 2.24 | 2.11 | 1.96 | 1.91 | 1.84 |
| **14** | **278.2** | 20.58 | 11.14 | 8.15 | 5.30 | 3.66 | 3.18 | 2.83 | 2.64 | 2.50 | 2.39 | 2.32 |
| **15** | **297.3** | 25.31 | 14.54 | 10.37 | 6.72 | 4.77 | 3.99 | 3.61 | 3.31 | 3.14 | 3.02 | 2.90 |

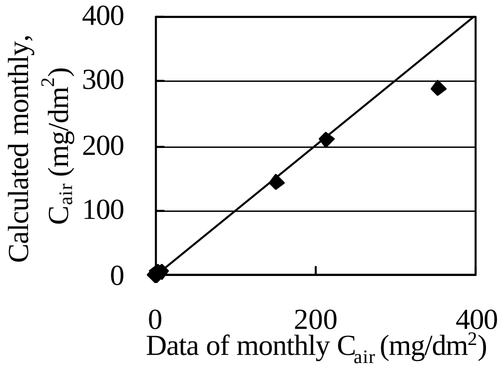
**Table 4.3.2:** The example of calculation method in order to obtain the total chloride content in $mg/dm^2/month$

| Time hr | Wind m/s | Eff wind | B*C m/s | Eff dist | Eff dia. | Eff Volume | Peak weight | Max size at seashore | SD' | Z value | area norm dist | Hourly Weight Cl | Wind direction |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1st | 0 | 0 | 0 | | | | 0 | 0 | 0.00 | 0.00 | 0.0000 | 0.0000 | - |
| 2nd | 1 | 0 | 0 | | | | 0.0075 | 12 | 4.18 | 0.00 | 0.0000 | 0.0000 | N-E |
| 3rd | 2 | 0 | 0 | | | | 0.06 | 33 | 11.50 | 0.00 | 0.0000 | 0.0000 | N-W |
| 4th | 1 | 0 | 0 | | | | 0.0075 | 12 | 4.18 | 0.00 | 0.0000 | 0.0000 | N-E |
| 5th | 1 | 1 | 1 | 209 | 3 | 1E-17 | 0.0075 | 12 | 4.18 | -2.15 | 0.0157 | 0.0002 | N-W-W |
| 6th | 0 | 0 | 0 | | | | 0 | 0 | 0.00 | 0.00 | 0.0000 | 0.0000 | - |
| 7th | 1 | 0 | 0 | | | | 0.0075 | 12 | 4.18 | 0.00 | 0.0000 | 0.0000 | N |
| 8th | 1 | 1 | 1 | 86 | 4.5 | 5E-17 | 0.0075 | 12 | 4.18 | -1.79 | 0.0364 | 0.0005 | S-S-W |
| 9th | 1 | 1 | 1 | 80 | 5 | 7E-17 | 0.0075 | 12 | 4.18 | -1.67 | 0.0471 | 0.0007 | S-W |
| 10th | 2 | 1 | 2 | 86 | 12 | 9E-16 | 0.06 | 33 | 11.50 | -1.83 | 0.0339 | 0.0041 | S-S-W |
| 11th | 2 | 1 | 2 | 86 | 12 | 9E-16 | 0.06 | 33 | 11.50 | -1.83 | 0.0339 | 0.0041 | S-S-W |
| 12th | 2 | 1 | 2 | 86 | 12 | 9E-16 | 0.06 | 33 | 11.50 | -1.83 | 0.0339 | 0.0041 | S-S-W |
| 13th | 1 | 1 | 1 | 80 | 5 | 7E-17 | 0.0075 | 12 | 4.18 | -1.67 | 0.0471 | 0.0007 | S-W |
| 14th | 2 | 1 | 2 | 86 | 12 | 9E-16 | 0.06 | 33 | 11.50 | -1.83 | 0.0339 | 0.0041 | S-S-W |

| 744th | | 8 ← | Summation of data from 1st hour to last hour in a | → 0.0185 $(mg/dm^2/month)$ |
|---|---|---|---|---|

In **Table 4.3.2**, the calculation of airborne chloride accumulation in a month has to consider in every hour. The wind speed in each hour is set as a constant with a direction. In the example, S-W direction is the effective wind direction for this location. The wind in each direction is calculated using **Eq.4.3.11**.

The wind without efficient direction is set zero value in the column of (Eff. Wind). The procedure in order to obtain the hourly chloride content is calculated using **Eq. 4.3.9-4.3.10**. Finally, the total chloride content in a month and average value in a day are obtained for verifying with the investigated data [1]. It is noted that the investigated data is the salt content which has to covert to the value of chloride content before the verification. In the verification, the samples, where are located at seashore, have to be generally assumed at 30m as the location of settlement the apparatus. The result of verification shows in **Fig. 4.3.8**.




| Data Notes | X(m) | Data | Cal. |
|---|---|---|---|
| Shikoku-May | 80 | 7.5 | 6.0 |
| Hokaaido-Dec | 20 | 213.2 | 210.0 |
| Shikoku-Aug | 200 | 0.7 | 2.0 |
| Shikoku-Apr | 400 | 0.4 | 1.2 |
| Shikoku-Nov | 50 | 0.4 | 1.2 |
| Kochi-Oct | 30 | 2.1 | 4.0 |
| Kochi-Oct | 100 | 0.6 | 1.8 |
| Kochi-Oct | 300 | 0.3 | 1.0 |
| Okinawa-Sep | 50 | 352.8 | 288.3 |
| Chuukoku-Dec | 50 | 150 | 144.0 |

**Fig. 4.3.8:** The verification by hourly simulation in selected samples

The overall systematic calculation is expressed in **Fig. 4.3.9** and shows the procedures of calculation. The 10 individual data were used to verify the model. It is very complex to simulate each case by hourly data in a month or year. The standard environmental condition should be created for easier simulation. This method is proposed in order to reduce the simulation process. Firstly, the standard environments are separated into 4 zones as below

**Zone 1:** Okinawa area

**Zone 2:** Japan-Sea coastline (Hokkaido to Niigata Prefecture)

**Zone 3:** Pacific Ocean Coastline

**Zone 4:** Chuubu to Nagasaki

The 4 zones are separated as shown in **Fig. 4.3.10** depending on the characteristic of environmental conditions and level of severity. The separation of severity has been recommended into 3 zones of Okinawa, Japan Sea coastline and others [19-22].

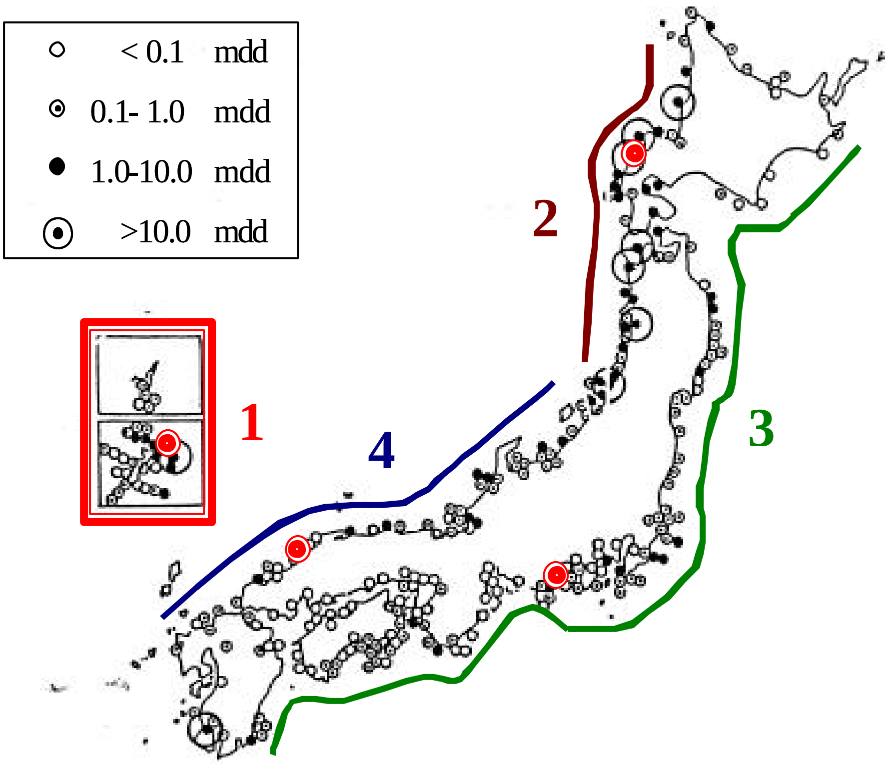



**Fig. 4.3.10:** The separation of 4 severe zones on chloride attack around Japan.

The 4 red marks in **Fig. 4.3.10** represent the selected environmental conditions in each zone. The area is selected in a moderate severe region of each zone and the weather condition is selected in year 1985 according to the date of investigated data. The data of the environmental condition are obtained by the observation of government section (See www.data.kishou.go.jp). The providing of average data in different time and locations are wind speed, wind direction, rain, sunshine hours, humidity, temperature, and etc. The standard weather condition is created due to the information observed in a zone. Firstly, the monthly effective wind speed is calculated by referring to **Table 4.3.2**. The monthly average value is done by

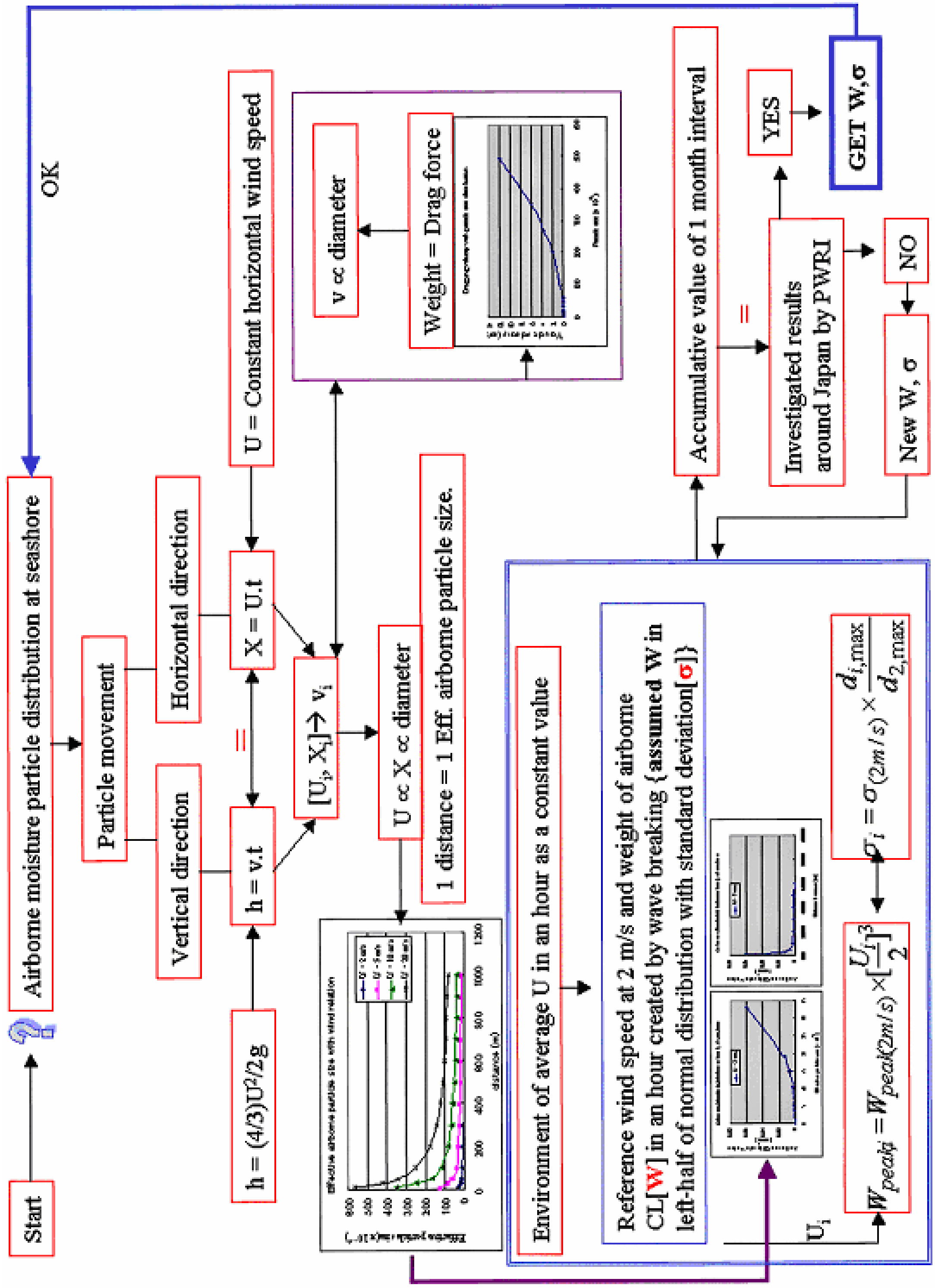



Fig. 4.3.9 Schematic calculation of airborne chlorides distribution

$$U_{eff} = \Sigma U_e / \Sigma r_e \tag{4.3.12}$$

where, $U_{eff}$ is monthly effective wind speed with equivalent airborne chloride (m/s)

$\Sigma U_e$ is monthly summation of wind only in the efficient wind directions (m/s)

$\Sigma r_e$ is monthly summation of efficient wind directions (hrs)

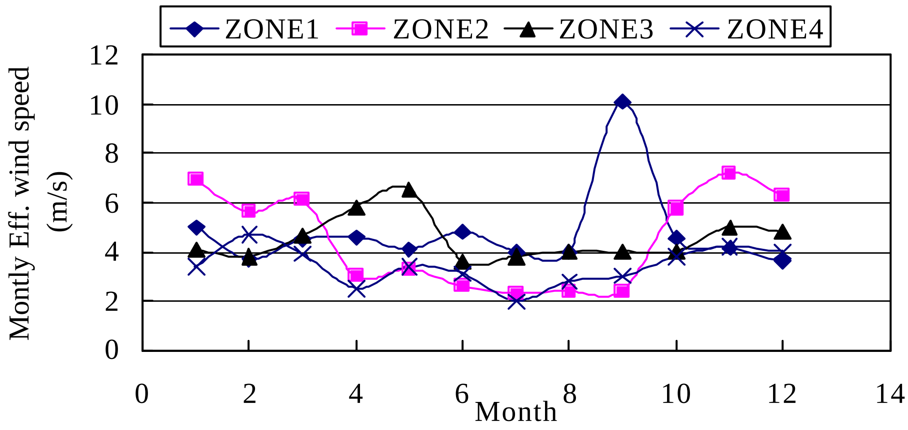



**Fig. 4.3.11:** The effective wind speed in monthly value in 4 zones

The effective wind speed, $U_{eff}$ in **Fig. 4.3.11** is calculated and found that it is higher than the average wind speed. The $U_{eff}$ is proved as an equivalent of chloride content and verified in **Fig. 4.3.12**.

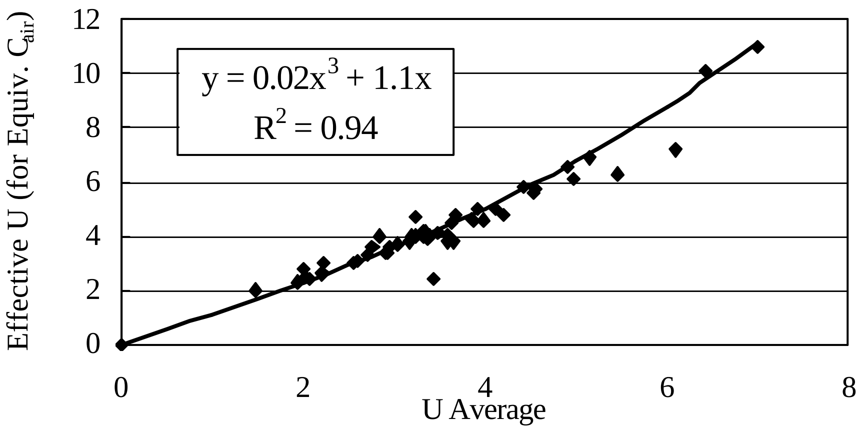



**Fig. 4.3.12:** The verification of effective wind speed and average wind speed

Next, the numbers of efficient wind hours is averaged daily and used for analyzing the efficient wind speed as described above. The summarization of results for all 4 zones is shown in **Fig. 4.3.13**. The figures in each zone are consisted of the average wind speed in each month and the effective wind direction averaged per days.

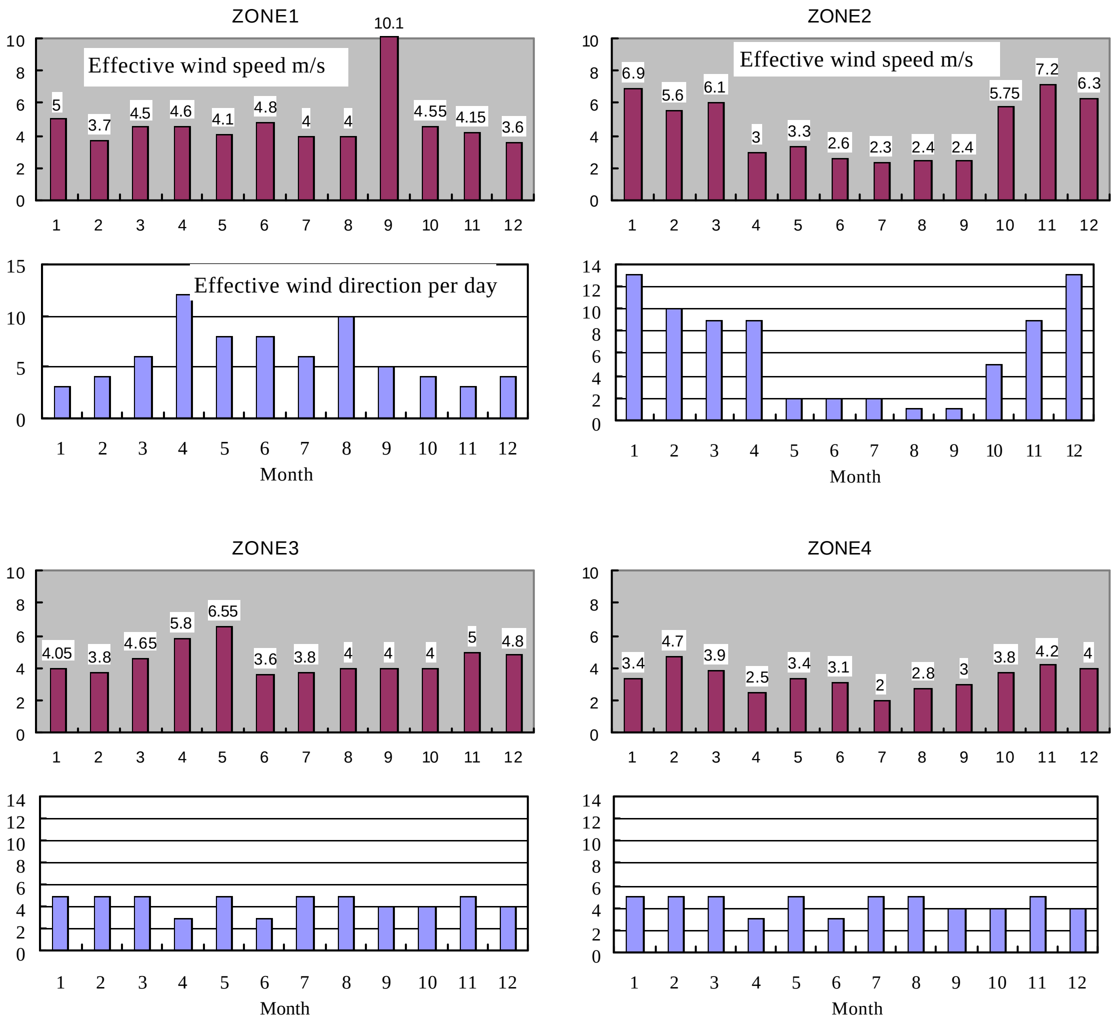



**Fig. 4.3.13:** The effective wind speeds (m/s) and hours of effective wind (hrs/day)

## 4.4 Verification on airborne chlorides formation and transportation

The uniform environmental conditions in **Fig. 4.3.13** are used to calculate the chloride contents in each month and verify with the investigated data of accumulative airborne chlorides. Raining period is no effect to the transportation of airborne particle to structures. The data was classified into various distances and only the data at distance of 0m, 100m and 500m are shown. In zone 1 to 4 (**Fig4.4.1-4.4.4**), some months are used the average value for comparison excluding the severe months in a year. In zone1, the most severe is in September due to storm effect; however this analysis is lower in this month. It can be said that the calculation is underestimated under the environment during storm period as shown in **Fig.4.4.1**. The storm affect to the wave energy which provide large effect to the amount of airborne particle formation in the atmosphere after wave breaking. In zone 2, the winter season show high chloride content according to the high wind speed during this time. In this case, the calculated results are also underestimated and illustrated in **Fig.4.4.2**. However the formula of wind speed relationship in third power is changed to the forth power, the overestimated of data is certainly too high. The optimum wind speed value is between third to forth power, but the third power is thought as the most accurate relationship in this study.

The calculation of the results in four zones is calculated without the effect of height. In general the height effect can be modified as the equivalent to the distance according to the calculating procedure described above. The airborne chloride in height 5m- 10m has not so large variation of chloride content. The available at the same distance in a separated zone is plotted together in order to show the macro-scale comparison of the computational model. The investigated results by PWRI have no supporting data on the exact position and real scenery at seashore area. Again, the settlement of the apparatus may not set exactly in the effective wind direction. In summary, three unknown parameters, which cause the scattering of data in verification, are height effect, seashore scenery, and settlement of the equipment. Moreover the effect due to residual wave energy acting on the airborne formation is also considered as further study of this study.

In order to understand the scattering level of overall data comparing with the calculation results, the data all around Japan are plotted by separating in macro-scale into 4 zones as shown in **Fig.4.3.10**. The comparison of 1-year accumulative airborne chlorides for all available data by PWRI 1988 is illustrated in **Fig4.4.5**. The further study on airborne chlorides formation is vital for reducing the scattering of data.

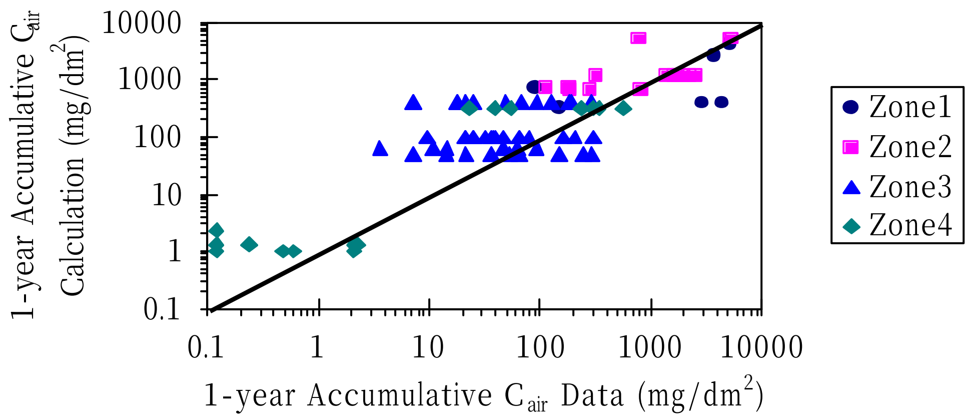



**Fig.4.4.5** Verification on 1-year accumulative airborne chlorides for overall data by PWRI

**ZONE 1**

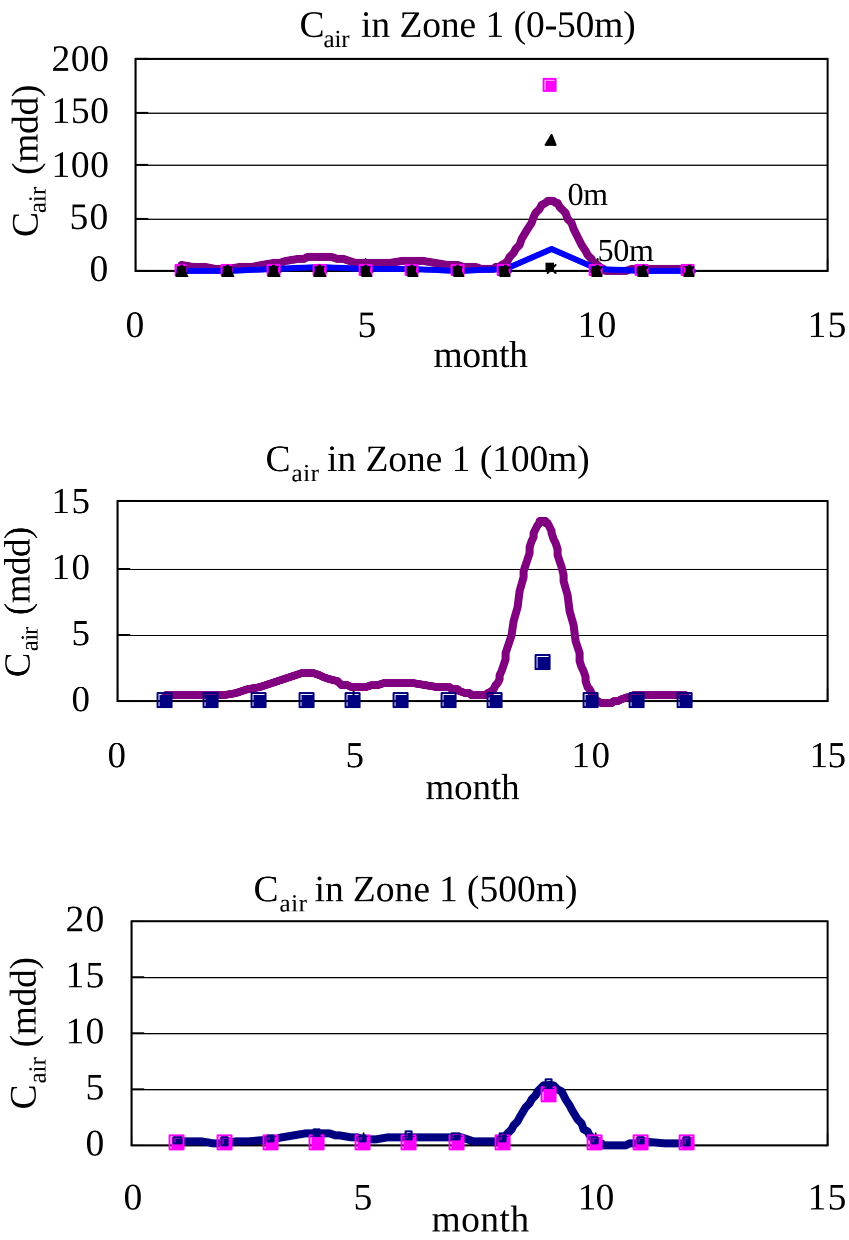



**Fig.4.4.1:** Verification of Zone 1 in Okinawa area. (Data from PWRI, 1985 [1])

**ZONE 2**

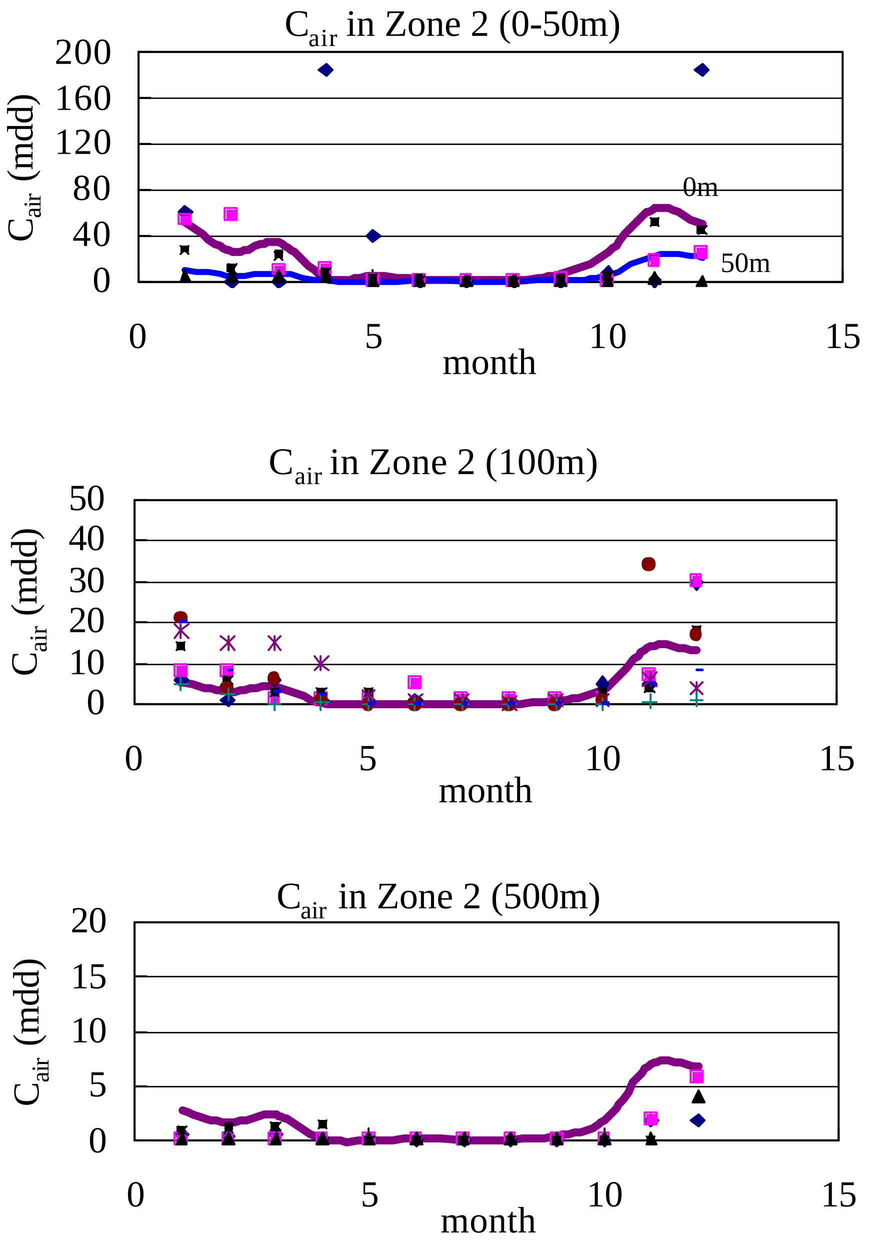



**Fig.4.4.2:** Verification of Zone 2 in Japan Sea coastline. (Data from PWRI, 1985 [1])

## ZONE 3

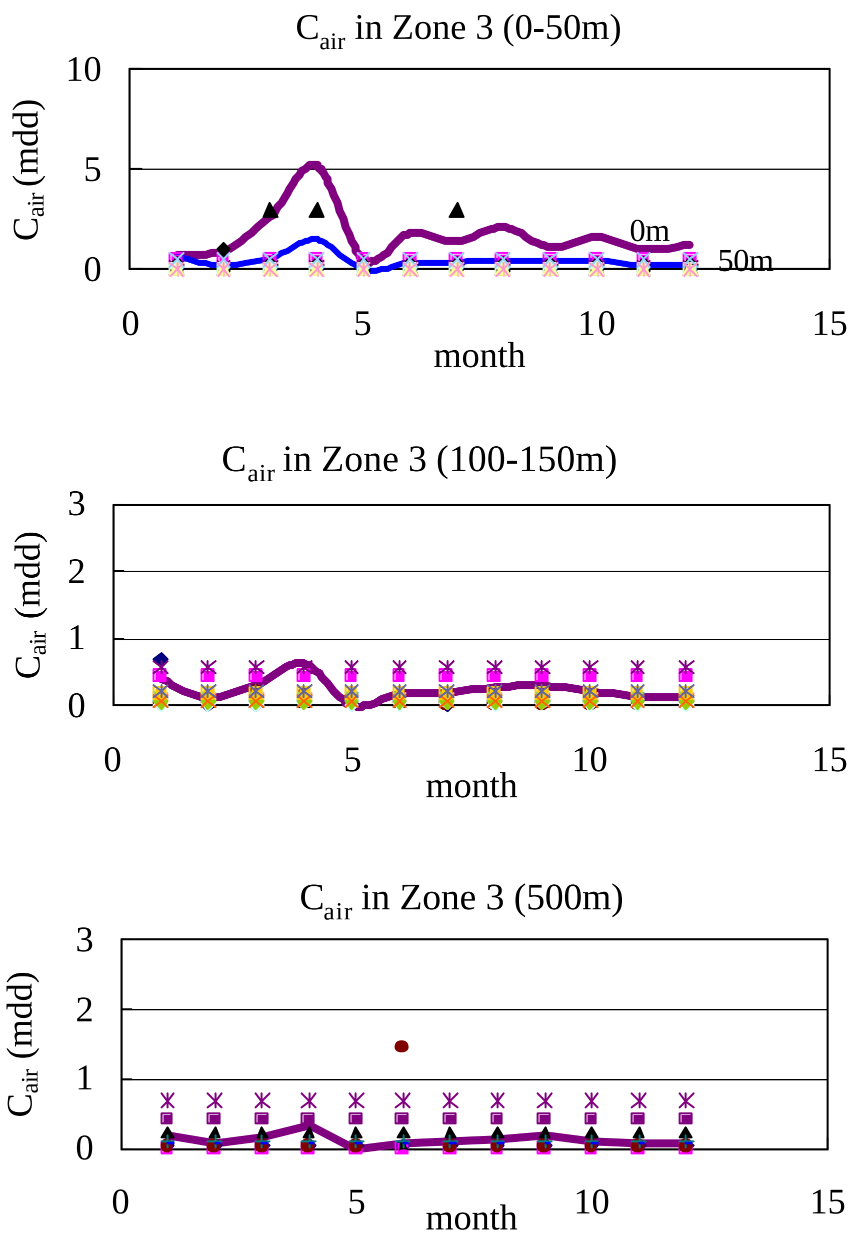



**Fig.4.4.3:** Verification of Zone 3 in Pacific Ocean coastline. (Data from PWRI, 1985 [1])

## ZONE 4

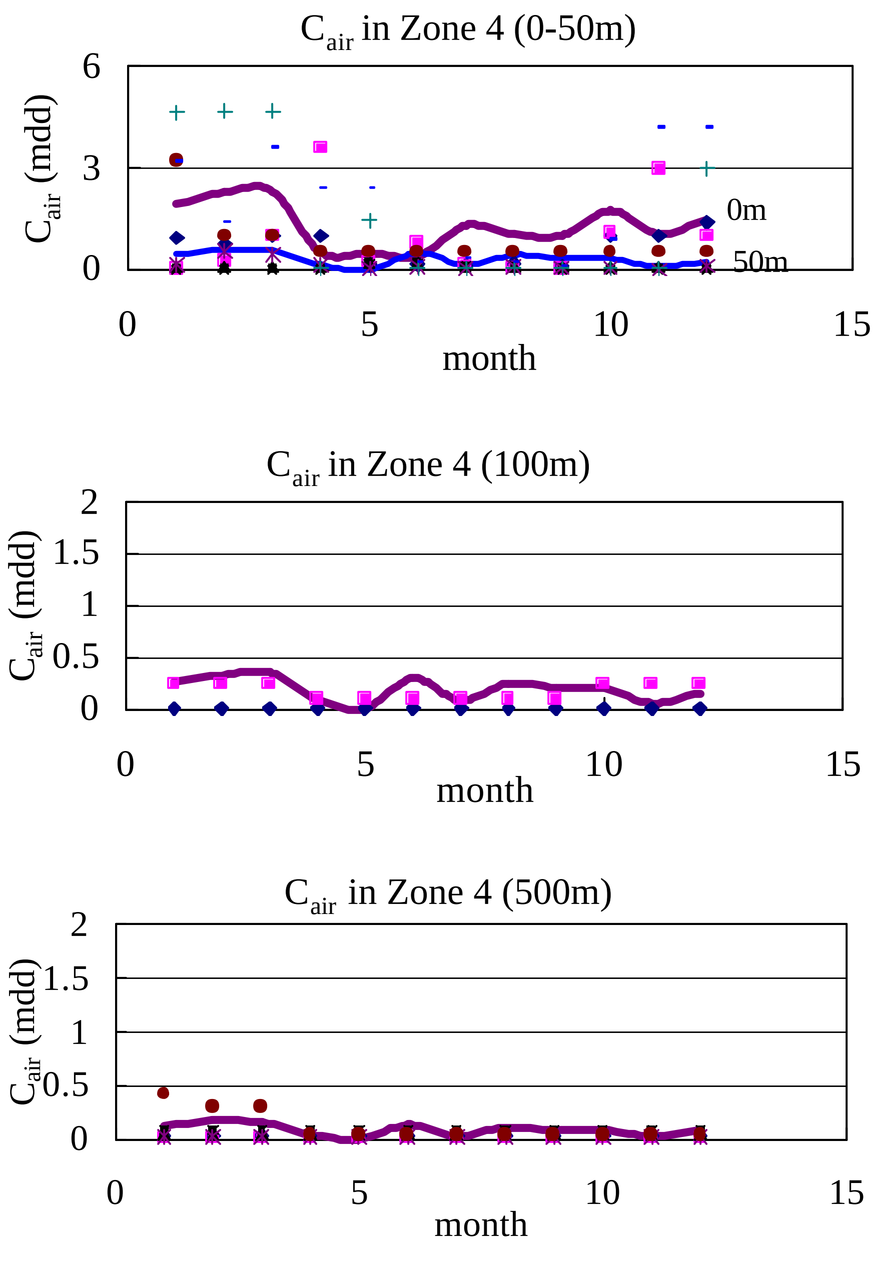



**Fig.4.4.4:** Verification of Zone 4 in Chuubu and Chuukoku Area. (Data from PWRI, 1985 [1])

## 4.5 Model Modification

The model presented above is the average model with free space transport in the atmosphere. The modification is necessary due to the scenery of the structure allocation. Firstly the costal landscape and artificial seawall are considered as in **Fig.4.5.1**. The recommendation on consideration of this difference is done by modifying the parameter of β in **Eq.4.2.2**. The natural or artificial offshore topography such as sea slope and concrete wave breaking wall in various angels and heights influence to the initial flying height.

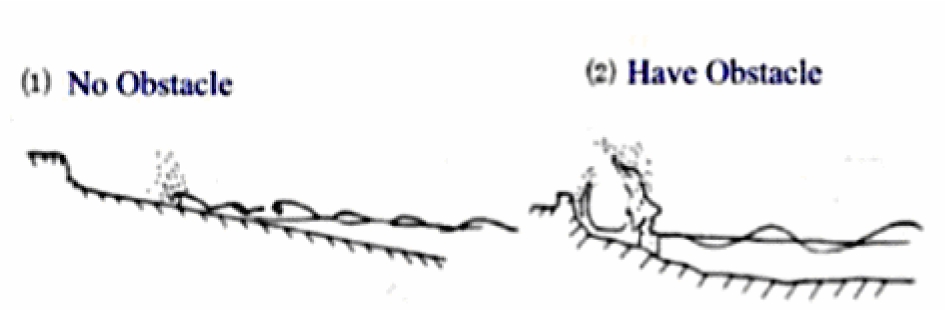



**Fig.4.5.1:** Sea-based landscape and seawall influence aerosol formation

Besides, the amounts of airborne chlorides formation in case of with and without obstacles for wave breaking along seashore are different. The modification on the amount of airborne chlorides in **Table 4.3.1** is necessary. The modification factor on the amount of airborne chlorides is proposed as R(d) in **Eq.4.5.1**.

$$C'_{air,hr} = C_{air,hr} . R(d) \qquad (4.5.1)$$

where, $C'_{air,hr}$ is modified airborne chlorides after obstruction (mg/dm$^2$/hr)

$C_{air,hr}$ is free transport airborne chlorides in **Table 4.3.1** (mg/dm$^2$/hr)

R(d) is modification factor due to obstacle

R(d) is the modification factor due to 2 main items of the obstacles for wave breaking in the sea and the obstacles inland along the distance from seashore. R(d) is the parameter to modified the free space transportation proposed in the Section 4.2-4.3. One of the investigated results is studied for obtaining value of R(d) as illustrated in **Fig.4.5.2**. The R(d) value is approximated by analyzing the reduction on the amount of airborne chlorides in a distance due to the residents, buildings and natural topographies. If the obstruction is constructed at 100 meter from seashore, the value of R(d) is

$R(d) = 1.0$ from 0 meter to the location of an obstacle

$R(d) = 0.4$ after passing an obstacle

R(d) is not always fixed as a constant value, thus many factors affecting to the transportation due to variety of obstacles. For the achievement of R(d), many investigated data should be considered and analyzed as the further study of this study.

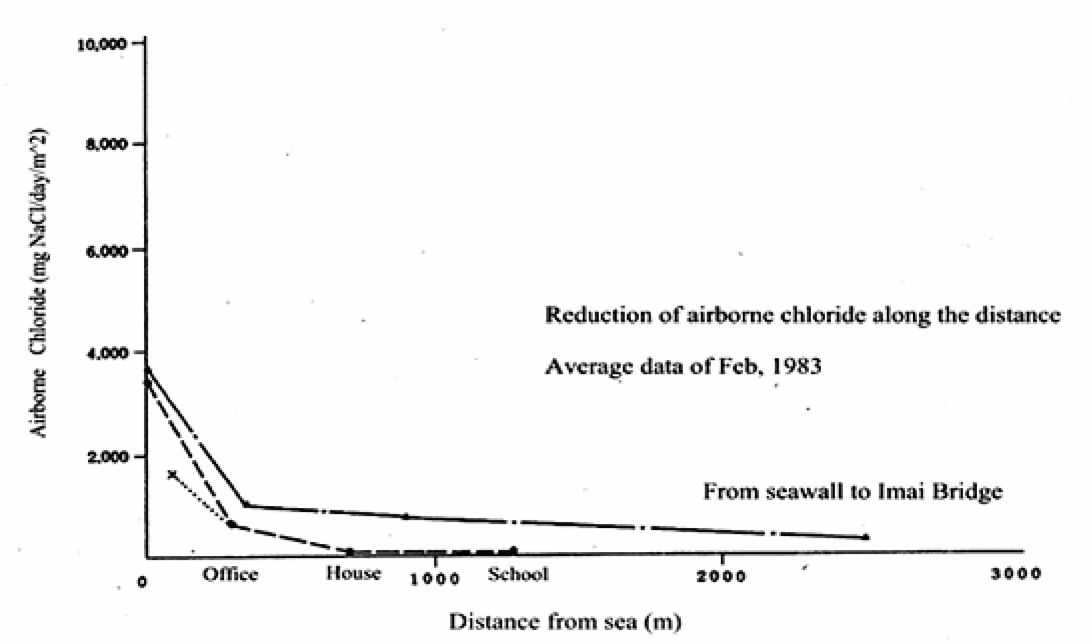



**Fig.4.5.2:** The investigated of the airborne chloride transport in the obstacle effect [19]

# CHAPTER 5

# Model of accumulated chloride concentration on the surface of concrete

## 5.1 Introduction

The model in this chapter is shown the accumulated chloride concentration with the parametric study and verification as shown in **Fig.5.1.1**

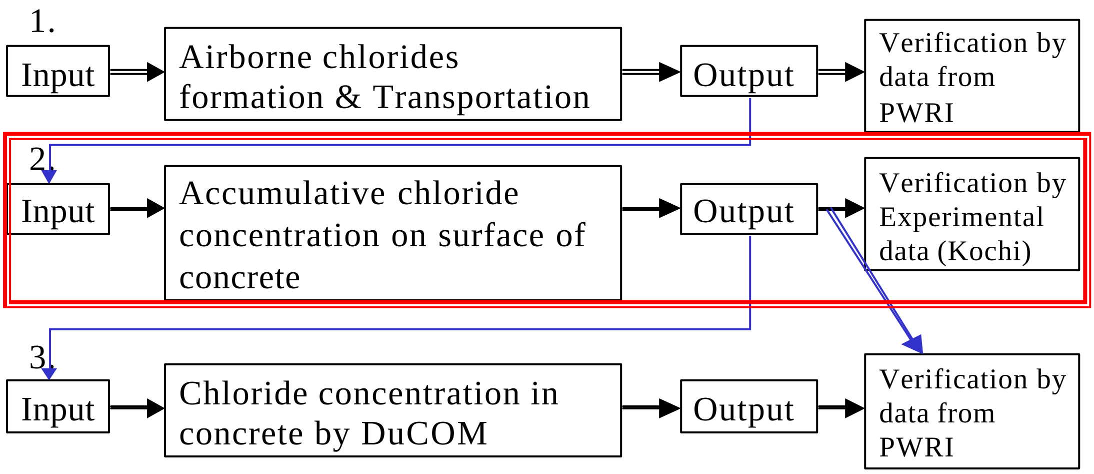



**Fig.5.1.1:** Schematic model of accumulative chloride concentration

The simulation in Chapter 4 shows that the airborne transport mechanism to a certain distance is known as in the function of wind speed in third power. In general, the amount of chloride concentration in concrete for the structures near seashore should be high. This causes by the amount of airborne chlorides transport to the structures. The airborne chlorides transported with the wind blow are adsorbed on the surface of concrete structures. The airborne chlorides are transported with the water particles to the surface of structures, so the absorption to the pore structure in the boundary layer happens. The literatures were proposed the boundary layer as 1cm depth from surface of concrete in unit of $kg/m^3$. This definition of the boundary layer was recommended because of unknown amount of airborne chlorides. The chloride concentration inside concrete averaged 1 cm depth from surface is represented as the boundary layer. Once, the amount airborne chlorides transported to the surface of structures are known, the new definition of boundary layer is more suitable. The boundary layer is thought as the layer which is the adsorption layer of airborne chlorides. The boundary layer in this study is defined as the adsorption layer in the depth of 0 to 1mm from surface of concrete. The rough and smooth surfaces have the boundary layer about 1mm and 0.08mm, respectively. The unit of chloride concentration in the boundary layer is also in kg per volume of concrete in $m^3$. In the boundary layer, the chloride concentration in this layer is due to the amount of airborne chlorides transported to it with neglecting of diffusive phenomenon into concrete. The reason that the amount of chloride concentration at surface of concrete is necessary is to use for calculating the chloride concentration in concrete. The DuCOM program can simulate the chloride penetration into concrete if the chloride concentration, temperature and relative humidity at the boundary layer are known. In this paper, the chloride concentration in the boundary layer is the same as the meaning of chloride concentration at surface of concrete.

Firstly, the chloride concentration in the boundary layer might be easily calculated by knowing the amount of the amount airborne chlorides adsorbed on surface. The conversion of the amount of airborne chlorides in unit of mg per unit area per time to the chloride concentration in the unit of kg per unit volume of concrete is vital. By this methodology, the structures located near seashore should have high chloride concentration on the surface of concrete. However, PWRI examined the chloride concentration in concrete and found that the retaining walls along seashore area in two different locations have large different chloride contents in concrete. Two examples of investigated result are done in Yamagata and Ichikawa prefectures which both are constructed near seashore as shown in **Fig.5.1.2**. Two structures at the same distance are totally different on the chloride concentration in concrete.

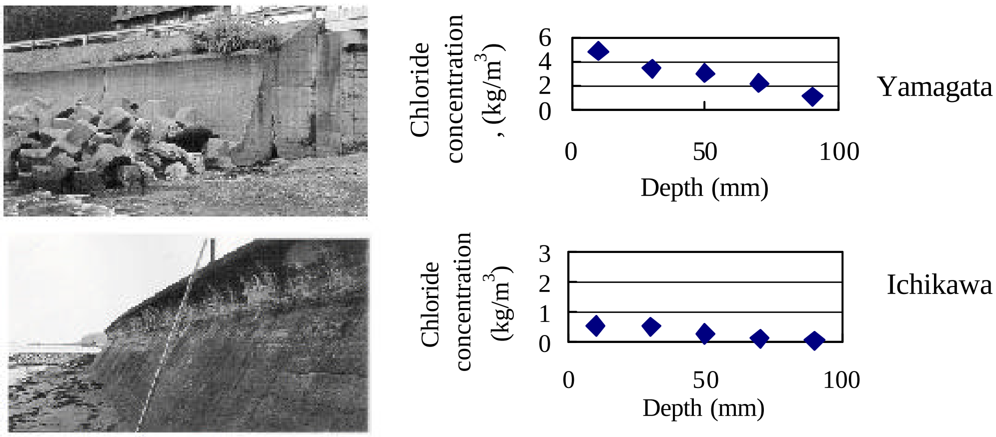



**Fig.5.1.2** Examples of investigated chloride distributions at seashore by PWRI

It is very necessary to study on what the main parameter causes the different of chloride concentration in concrete in the same location and type of structure. The environmental parameter and the structure itself are both considered in order to explain this phenomenon. Many parametric studies such as, temperature, relative humidity, amount of airborne chlorides, the deteriorated level of crack and concrete property are not able to explain clearly which are the most effective parameter. Finally, raining is thought as the parameter which is able to explain this phenomenon evidently. None of the literature had ever investigated the raining effect to the removal of chloride concentration in the boundary layer. Several structural members out of the roof are subjecting to rainfall during raining, and having various surface roughness. The experiment on site is necessary for investigate the chloride concentration in boundary layer with time history. After that, the parametric observation of rain and wind effects related with the accumulation of chloride concentration in the boundary layer is accomplished. Next is the creation of the model on accumulative chloride concentration in the boundary layer with time dependence. As the results, the model is applicable to predict amount of accumulative chloride concentration in the boundary layer in any locations of Japan, if the environmental conditions are known.

## 5.2 Experimental outlines

### 5.2.1 The examination of chloride distribution in surface layer

At the real surface of the structures, the surface concrete has to take out to test for the chloride concentration. Firstly, the investigated area on the selected surface of structure is set the size of 10 x 10 cm dimensions using sand paper for 1g abrasion. Using of sand paper is better to stick with a cubic bar for uniformly abrasion. At the same observed 10x10 cm section, the samples are taken for 4 layers more with 1g each. Some of samples were done in the 3-times bigger area and taken 3g each, such as 15x20 cm, or 10x30 cm. The bigger area was taken in order to provide three times average. However, the results are compared and there is no much different in any area. In conclusion, the area of 300$cm^3$ is a better choice for guarantee accuracy. The dustpan with the wind blocking is used to collect the sample falling down after abrasion. The initial and final weight of sand paper in each layer should be weighed for deduction the influent weight of the particles from sand paper out of taken samples. Many existing structures in Kochi area have investigated with the several of distance from sea, types of structure, and outdoor or indoor members. The different of surface conditions are also investigated in 3 conditions of smooth, normal and rough as shown in **Fig.5.2.1**.The taken sample is used for testing the acid soluble chloride concentration in samples by the titration method. In this method, the result is the acid soluble chloride content and thought as the total chloride concentration in unit of % weight of sample. The chloride concentration in $kg/m^3$ of concrete is calculated by assumed that unit weight of concrete is approximately 2300 $kg/m^3$ for all samples.

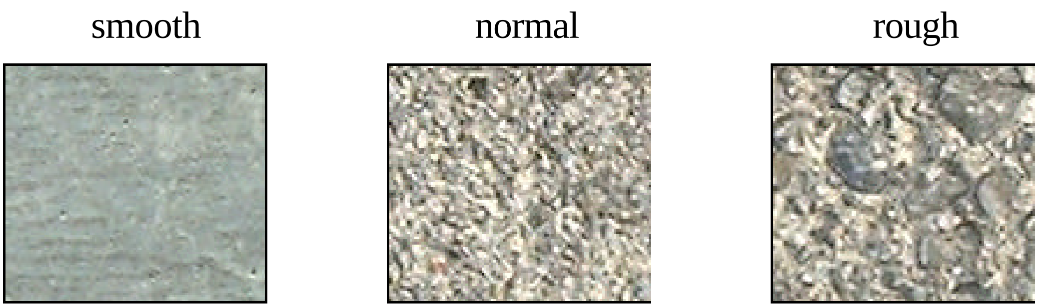



**Fig.5.2.1:** Three surface roughness conditions of investigated structures

The examination was done in three locations with difference distance, and surface roughness observed in a location, as well. **Fig.5.2.2-5.2.4** are three observed structures, which are concrete block, bridge pier, and box girder, pier and foundation, respectively. In the **Fig.5.2.2**, the structure is concrete stairs, which is able to investigate normal and rough surface conditions. On the right side of concrete stairs, they turn in

**Fig.5.2.2:** The investigated structure in Maehama at 30m from seashore

90° to the facing-to-sea direction. Thus rough surface on difference wind direction is tested for wind direction effect. There is none of smooth surface in this location according to the age of this structure is long term.


**Fig.5.2.3:** Monobe Bridge pier structure on ground at distance of 300 meters from sea

**Fig. 5.2.4:** Box girder, Pier, and foundation in Yasu Town at distance of 100 meters from seashore

The structure in **Fig.5.2.3** is bridge pier of Monobe Bridge crossing the Monobe River, and the surface condition is smooth case. The scenery is quite clear from trees or residents except the bank. The structure in **Fig. 5.2.4** consists of three members of box girder, foundation and pier in Yasu town. All members are considered as smooth surface. This structure is quite new structure located at distance of 100 meters from seashore. The rain affects to box girder and foundation excluding pier. All structures are investigated with time history. It reminds that the examined surface would not abrade again.

### 5.2.2 The examination of Co by considering as the average of chloride in surface depth

The checking of surface roughness is very important of taking sample of the surface depth. The collected sample depends on the level of roughness until the smooth surface is achieved. The smooth surface is set as amount of concrete paste on surface. This can be explained as the taken layer until the aggregate is found. The surface paste is considered as high w/c and porosity, which is considered at the depth at most 0.08 mm. The normal and rough surfaces are occurred by erosion of smooth surface by raining. The degradation of smooth surface takes a several years to make concrete surface become rougher. The selected area is set a bigger area of 500 $cm^2$ and doing abrasion on selected surface till surface becomes smooth. Next, the weight of sample taken from surface should be weighed and deducted weight of sand paper, and then the amount of total weight could be estimated by the experiment in **Section 5.2.1**. The taken sample in this section is used to sieve for finding the distribution of sand particle to powder ratio. The max size from sieve analysis is defined as the roughness depth of the considered structures. Another means is using the automatic roughness sensor, which can detect the roughness during abrasion on surface. The roughness sensor used in this experiment to measure the roughness of concrete.

## 5.3 Experimental Results

The investigation of chloride concentration in the boundary layer is done using abrasion test using sand paper. The samples are examined on the surface of concrete within the specific area in 5 layers from surface. Each investigated layer is limited by the amount of taken sample weight (g). In **Section 5.2.2**, the relationship of weight of sample from abrasion test and surface roughness from the roughness sensor can be obtained, and it is used to represent the chloride concentration with the depth. At first, the examination results in each member of concrete stairs at 30 meters from average coastline from MSL are discussed. The results of normal and rough surface are illustrated in **Fig.5.3.1** and **Fig.5.3.2**, respectively. The investigation time is examined 6 times during Jun 20th to Sep 26th, which is in raining season. Both rough and normal surfaces are tested at the same dates for comparing roughness condition in the same environmental condition.

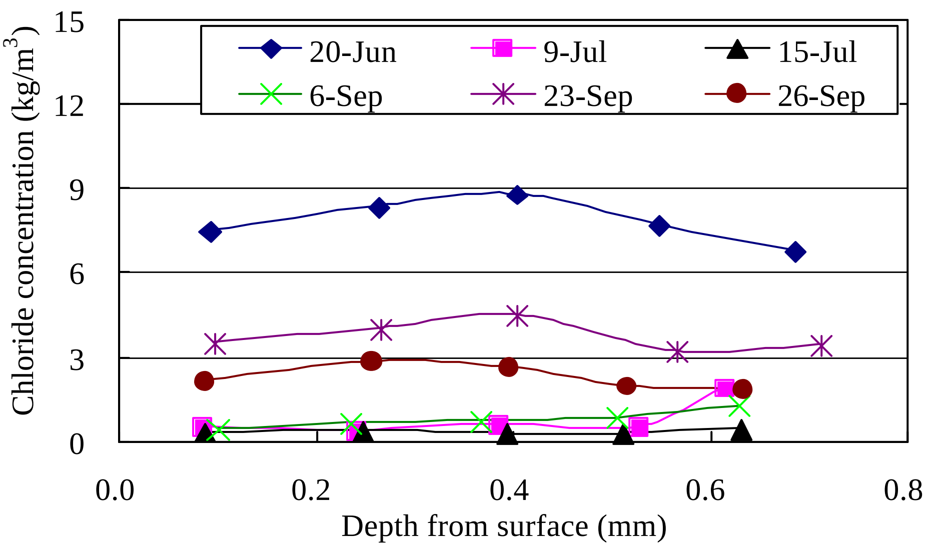



**Fig.5.3.1:** Experimental results in the normal surface (kg/m$^3$) with time dependent at Maehama, Kochi Prefecture (30m from seashore)

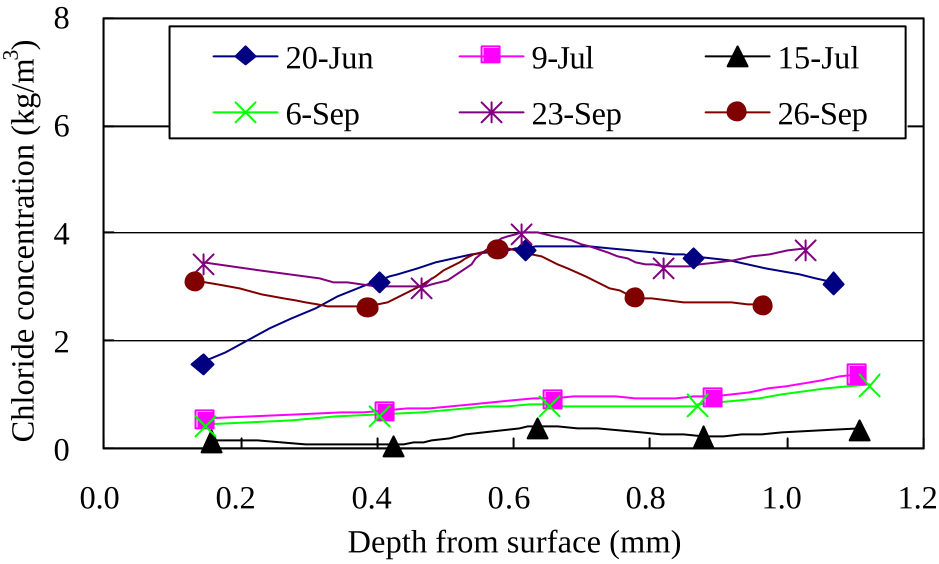



**Fig.5.3.2:** Experimental results in the rough surface (kg/m³) with time dependent at Maehama, Kochi Prefecture (30m from seashore).

These results on June 20th in both roughness show that the chloride concentration in normal roughness has higher value than it on rough surface. It does not mean that chloride adsorption in normal surface is more severe than rough surface. Surface roughness affect to the adsorption by the factor of specific surface area. High specific surface area affects both adsorbed and dissolved capability on surface of concrete. In order to analyze these two results, the raining amount before and during experiment is necessary as shown in **Fig. 5.3.3**. The amount raining in Kochi is large from May to August, thus chloride concentration at the surface is removed in a large amount proportional to the specific surface roughness of concrete. The amount of chloride concentration on the rough surface is removed in a large amount. As the results, the chloride concentration on June 20th is less. After June 20th, the chloride concentration is dramatically decreased due to raining until zero. In sunshine day, the accumulated chloride at surface started again, thus the chloride concentration the testing date should be considered according to actual environment.

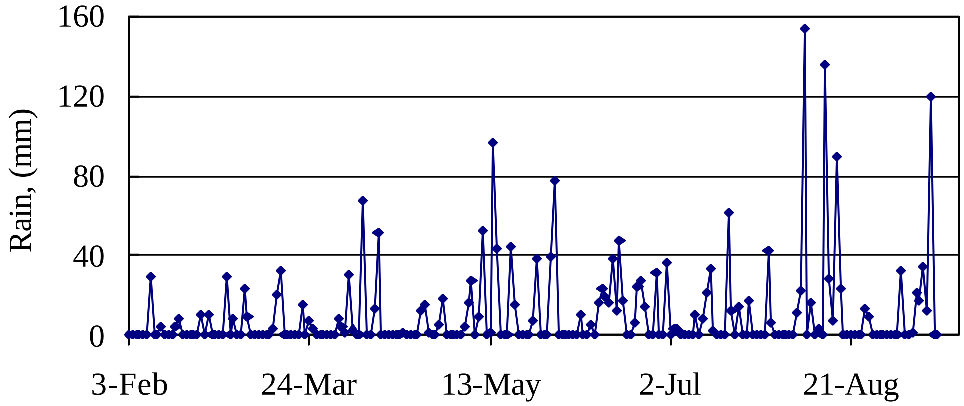



**Fig.5.3.3:** Amount of rain (mm) during Feb to Sep in Kochi prefecture.

At the Maehama, the surface, where is parallel to the south wind direction, is also examined. So the efficient wind direction is narrower and the accumulated chloride is less, though the raining effect is same. The result in this case shown in **Fig.5.3.4** is less than that in the rough surface of results described above.

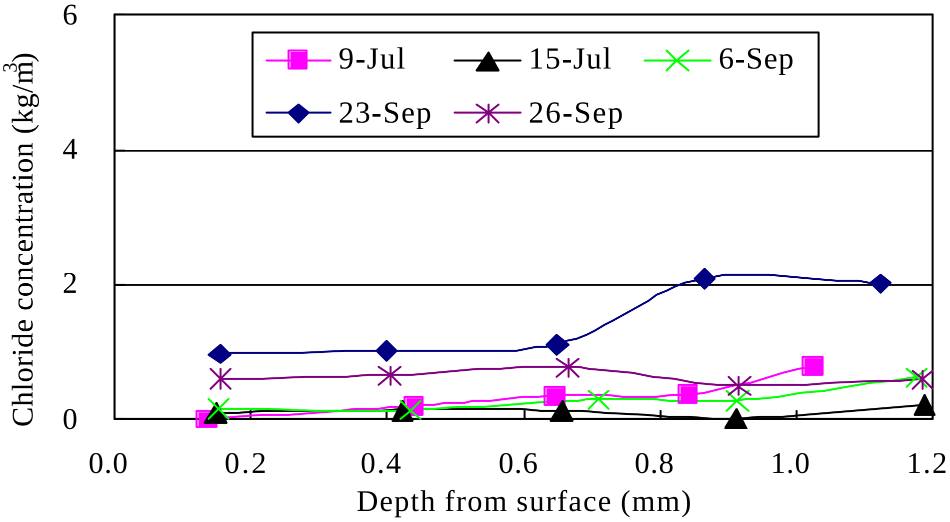



**Fig.5.3.4:** Experimental results on the rough surface parallel to South wind (kg/m$^3$) with time dependent at Maehama, Kochi Prefecture (30m from seashore).

Next the examination of the indoor pier structure in the farther distance at 300 meters from seashore. The experimental is still organizing continuously, but only two samples are shown at this moment in **Fig.5.3.5**. The distance relationship can be referred to the model in Chapter4 already, thus the experiment is applicable for verifying distance factor.

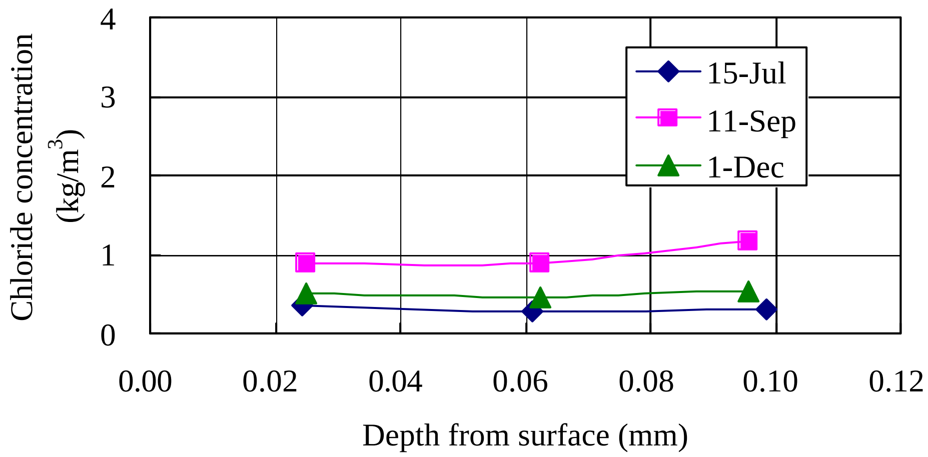



**Fig.5.3.5:** Experimental results on the smooth surface (kg/m³) with time dependent at Monobe Bridge, Kochi Prefecture (300m from seashore).

The age of Monobe Bridge was constructed 30 years ago, therefore the structure at 300m from seashore has very little severe and allow structure to corrode in very long time. This structure can be thought as non-damaged chloride attack through out up to 100 years. The additional experiment was done in Yasu Town at distance of 100 meters from seashore. Three types of different members of foundation, pier and box girder are shown in **Fig.5.3.6-5.3.8**, respectively. Again, these three members are used to explain the effect on distance at 100m, raining effect in difference conditions. The foundation is an outdoor structure subjected to 100% rain. Box girder is slope surfaces with have half of rain effect and only when efficient wind direction during raining occurred. The pier has none of rain effect at all. The surface conditions are all smooth surface with different strength due to structural types.

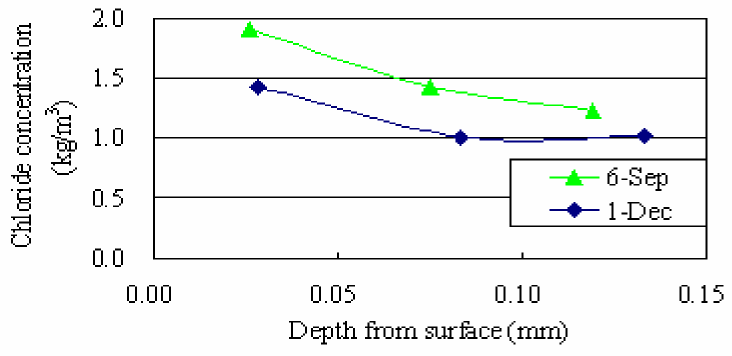



**Fig.5.3.6:** Experimental results on the smooth surface of outside foundation (kg/m3) with time dependent at Yasu Town, Kochi Prefecture (100m from seashore)

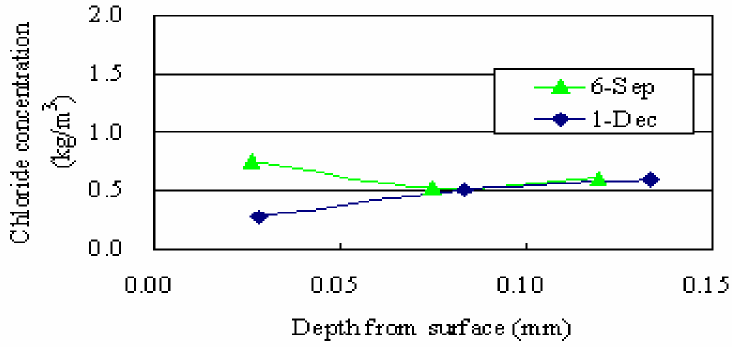



**Fig.5.3.7**: Experimental results on the smooth surface of pier (kg/m3) with time dependent at Yasu Town, Kochi Prefecture (100m from seashore)

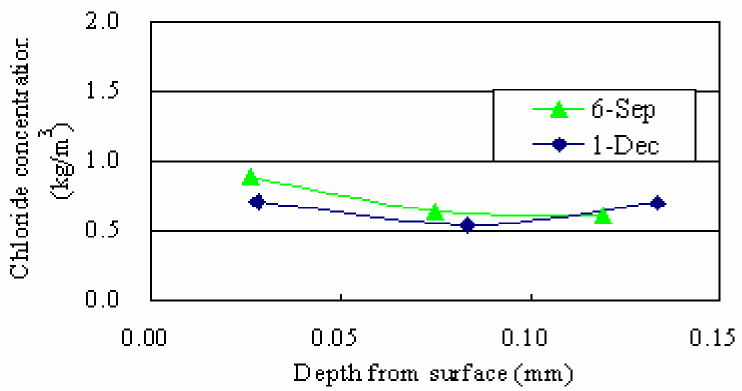



**Fig.5.3.8:** Experimental results on the smooth surface of girder (kg/m3) with time dependent at Yasu Town, Kochi Prefecture (100m from seashore)

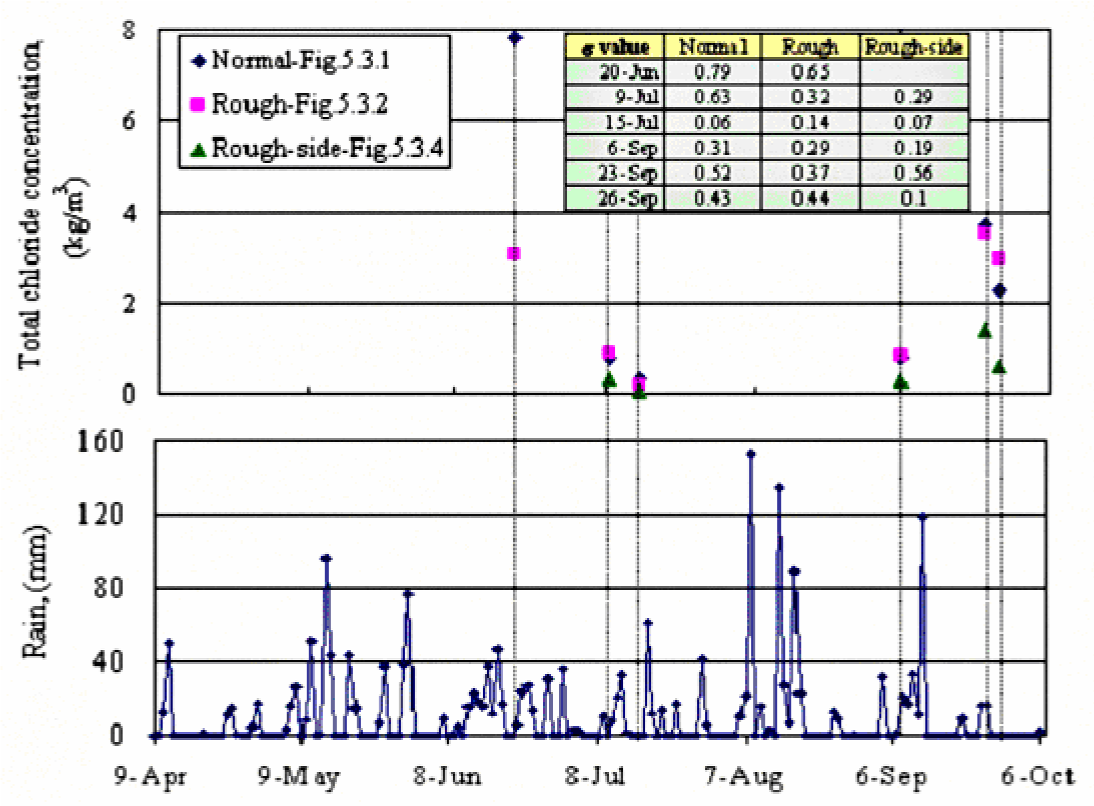



**Fig.5.3.9:** The time history of average accumulated chloride concentration, at Maehama, Kochi Prefecture

The chloride concentration along the depth from surface layer of concrete is almost same at the boundary layer of 0 to 0.8mm for rough and normal surfaces and 0 to 0.10mm for smooth surface. **Fig.5.3.9** shows the chloride concentration at surface of concrete averaged from the experimental results in **Fig.5.3.1**, **5.3.2** and **5.3.4**, and the standard deviation is also calculated. The table attached inside **Fig.5.3.9**, show the standard deviation of each experimental data. The maximum standard deviation of the average value is up to 0.8kg/m$^3$. The amount of chloride concentration after Jun 20$^{th}$ is decreasing with affected by raining duration. During the sunshine period, the increment of chloride concentration at surface of concrete can be seen during 6$^{th}$-23$^{rd}$ of Sep. During this period, the raining period is rare comparing with the sunshine period. From the results in **Fig.5.3.9**, the distribution of chloride concentration at surface of concrete is recognized that the raining effect is significantly removed.

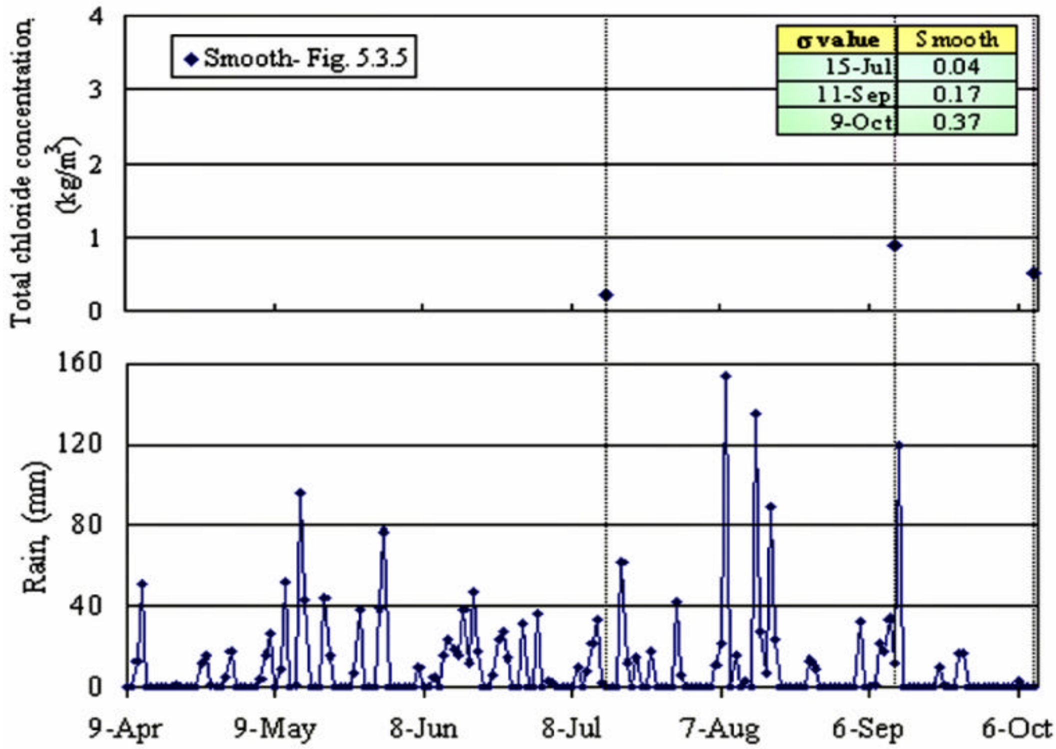



**Fig.5.3.10:** The time history of average accumulated chloride concentration, at Monobe Bridge, Kochi Prefecture

The average results of the experiment of the Monobe Bridge are shown in **Fig.5.3.10** with the same display as in **Fig.5.3.9**. The bridge pier of Monobe Bridge is located inside the roof; however the size of roof is not so wide. Sometimes with some strong wind in south directions, rainfall might affect to the removal of chloride concentration at surface of concrete. It is still in doubt on how strong wind has influence to the surface of bridge pier. Again, rainfall might effect to structure by making surface becoming wet condition. Rain might outcome the wet surface condition without removal of chloride concentration. This phenomenon results the rate of diffusion inside concrete, and the amount of chloride concentration at surface of concrete is reduced due to the diffusion into concrete. For the bridge in Yasu town, it was constructed recently, so the surface condition is durable.

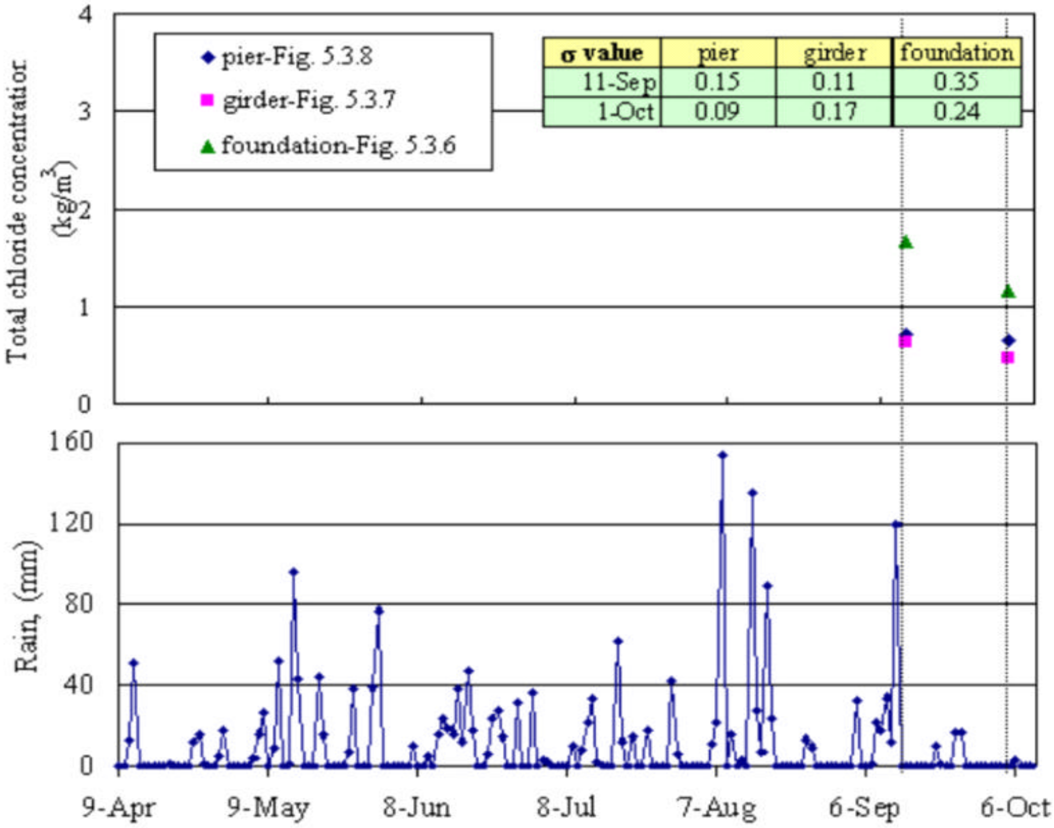



**Fig.5.3.11:** The time history of average accumulated chloride concentration, at Yasu, Kochi Prefecture

For the pier and box girder of this bridge, the results in **Fig.5.3.11** have no effect of rain acting on the surfaces, so the accumulation is gradually increasing without removal by rainfall. Only two points' investigation in this structure were done, and found that the rate of increasing the amount of accumulative chloride concentration at surface of concrete is very low. So, the examination period for indoor structures is not necessary to investigate in a short period.

## 5.4 Prediction model of annual accumulated chloride concentration.

The assumptions of this prediction model are the consideration of wind in hourly, and rain in daily. Moreover, the fact on the various surface roughness and structural types are added in this prediction model as well. The model provides the reference value of the increment of chloride concentration by wind, and declination due to rain in various surface conditions. The computation model considered the quantitative effect of environmental conditions and structural surface conditions. The accumulative chloride concentration in the boundary layer should be the functions of airborne chlorides, which is described in chapter 4, surface conditions of concrete and weather conditions such as rain and sunshine. The reference value is based on the experimental results in Kochi prefecture, thus the actual environment of Kochi prefecture is used in the verification. The average wind speed of Kochi prefecture only for the efficient wind speed is 3 m/s.

First of all, 1-year weather in Kochi prefecture is introduced. The average value cannot be used in analysis according to the fact that wind speed relationship with chloride accumulation is in third power. For simple explanation, the chloride accumulation in an hour of wind speed at 8m/s is much higher than its 4 hours of wind speed at 2 m/s. The best prediction is to make use of hourly wind speed for undoubted calculation. The efficient wind directions in Kochi prefecture are illustrated in **Fig.5.4.1** and the ratio of each wind direction is illustrated in **Fig.5.4.2**. The efficient wind direction is totally at 46.3% and South wind represents the effective wind direction in Kochi.

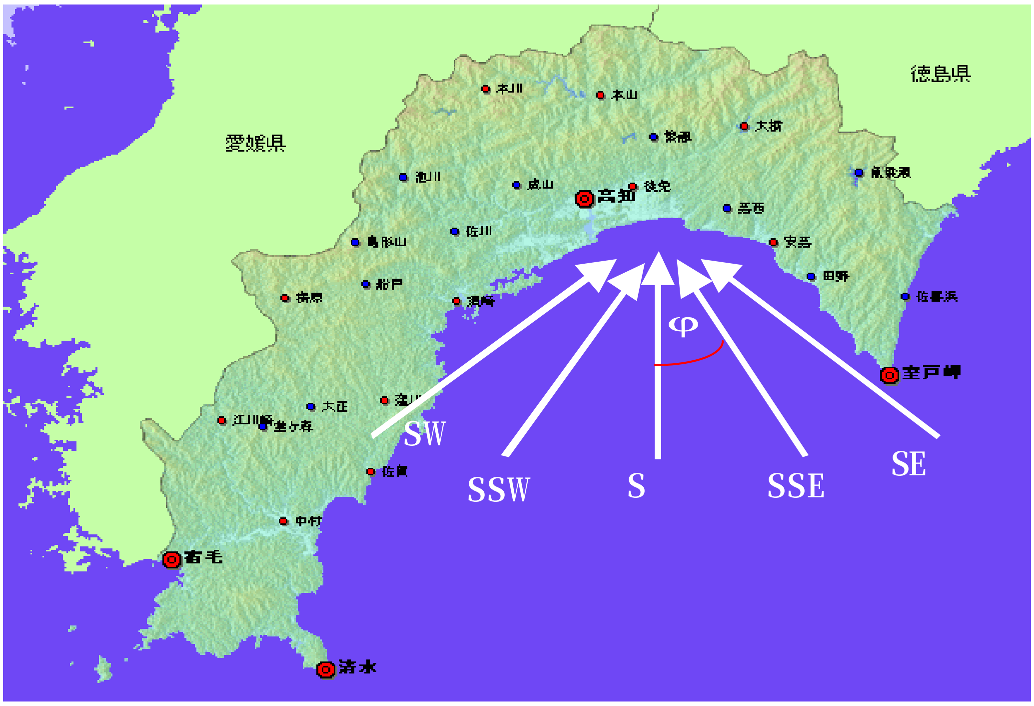



**Fig.5.4.1:** The efficient wind directions at seashore in Kochi prefecture.

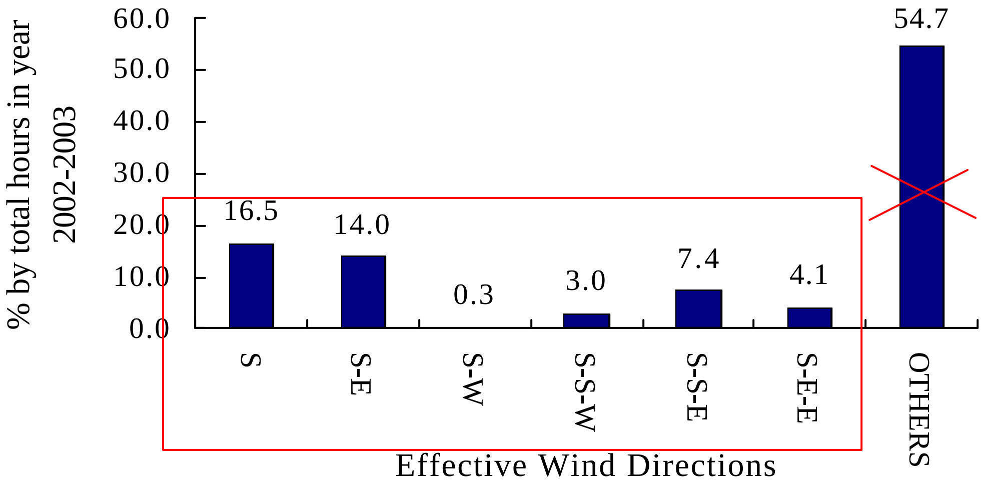



**Fig.5.4.2:** The ratio of wind direction in year 2002-2003

The model for calculating the accumulative chloride concentration in the boundary layer is simply proposed as the coefficient of accumulation per unit of wind speed. The amount of airborne chloride at wind speed 3 m/s is converted to the unit of $kg/m^3$ of volume concrete. The coefficients of accumulative chloride content are recommended as a constant value in a specific surface condition and raining effect at seashore. The recommended values are illustrated in **Table 5.4.1**. In this study, the shoreline is approximately set as 30m from the concrete obstacle constructed in the sea

**Table5.4.1:** Chloride accumulation in various conditions at seashore (about 30m from concrete wave breaking) with the constant wind speed at 3m/s ($kg/m^3$)

| Co Accumulation ($kg/m^3$) | Smooth | Normal | Rough |
|---|---|---|---|
| No rain / Little rain | 0.0003-0.002 | - | - |
| 50% Rain Effect | 0.004 | - | - |
| 100% Effect | 0.008 | 0.01375 | 0.0175 |

| Co Removal ($kg/m^3$) | Smooth | Normal | Rough |
|---|---|---|---|
| Little rain | -0.069 | - | - |
| 50% Rain Effect | -0.138 | - | - |
| 100% Effect | -0.276 | -0.45 | -0.65 |

For other wind speeds, the equation for calculating the coefficient of accumulative chloride concentration in the boundary layer is followed in **Eq.5.4.1**. The ratio of wind speed in the third power is regarded as the model described in chapter 4. The third power of the relationship between wind speed and surface chloride accumulation is referred to the **Eq. 4.3.9**. The discussion in chapter 4 expresses the amount of airborne chlorides in a distance related with the third power of wind speed, thus the coefficient of accumulative chloride concentration in the boundary layer should be in the same function.

$$\Delta C_{o,i} = \Delta C_{o,(3m/s)}.\ [U/U_{(3m/s)}]^3 \qquad (5.4.1)$$

where $\Delta C_{o,i}$ is coefficient of increasing surface chloride concentration at wind speed U

$\Delta C_{o,(3m/s)}$ is coefficient of increasing surface chloride concentration at wind speed 3m/s

Next, the amount of chloride accumulation to the surface of structure along the distance from seashore is predicted. The calculation of the coefficients of accumulative chloride concentration for a structure in a particular distance is directly related with the amount of airborne chlorides transportation. The coefficients proposed in **Table 5.4.1** are converted based on the amount of airborne chlorides of 0.10 $mg/dm^2/hr$ under the conditions of wind speed at 3m/s and the distance of 30m. The conversion of coefficients in the function of transported distance at a constant wind speed is shown below,

$$\Delta C_{o,x} = \Delta C_{o,(30m)}. [C_{air,x}/C_{air,30m}] \qquad (5.4.2)$$

where, $\Delta C_{o,x}$ is coefficient of accumulative surface chloride concentration at a distance

$\Delta C_{o,(30m)}$ is coefficient of accumulative surface chloride concentration at 30m from concrete wave breaking

$C_{air,x}$ is amount of airborne chlorides at a distance

$C_{air,30m}$ is the reference of the amount of airborne chloride at 30m from concrete wave breaking

The relationship between transportation distance and the coefficient of accumulative chloride concentration in the boundary layer in **Eq.5.4.2** is proposed for the effective wind direction. The different wind directions have been discussed in chapter 4, again the conversion of wind direction to the equivalent of transportation distance should be considered. After conversion of efficient wind directions to the transportation distance, the coefficient of accumulative chloride concentration in the boundary layer is obtained.

Then, the model of the removal of chloride concentration in the boundary layer by raining effect is considered. First of all, the raining effect on the removal of chloride concentration in the boundary layer should be understood. However raining effect is very complex and not well understood, yet. The model in this study is proposed on the some basic assumption such as,

1) The amount of raining (mm/hr) is independent with the removal of chloride concentration in the boundary layer. For example, the removal of raining at 2 mm/hr or 10 mm/hr is same.
2) The removal by raining has an effect in daily scale, because only raining duration in hours is not taken absolute effect into account. During pore solution in the boundary layer of concrete is absolutely fulfilled with water, the diffusion outward from inside concrete is significant. Also, a several hours between two periods of raining affect to the dissolving of chloride concentration out of the boundary layer. In the raining days, the amount of precipitation is quite small and continuous for whole day. Thus, the raining effect on the removal of the chloride concentration in the boundary layer is thought as a daily average value.
3) The removal of chloride concentration in the boundary layer depends on the roughness of surface. The removal of chloride concentration on rough surface is the largest due to the highest of specific surface area.
4) The structures are separating into 2 conditions of indoors and outdoors, which rain affect to the outdoor structures only. The raining will not affect the removal of

chloride concentration on indoor structure, except the rain drainage path passing to the surface.

From above consideration, the coefficients of removal chloride concentration in the boundary layer are recommended according to the surface conditions and structural circumstances as shown in **Table 5.4.1**.

For more understanding of target of this model, the 1-year accumulative chloride concentration is shown under the analyzing of actual environmental conditions. Due to the experimental organized in Kochi prefecture with various distances and structural members, the prediction of 1-year accumulative chloride concentration in the boundary layer is done for verifying the precision of this computational model. The prediction of 1-year accumulative chloride concentration for the smooth, normal and rough surfaces, and wind direction are shown in **Fig.5.4.3 (a)** to **Fig.5.4.3 (d)**. The calculation of accumulative chloride concentration in the boundary layer starts in the summer season in 2002. According to the experimental results, the amount of chloride concentration in the boundary layer is nearly zero after long duration of raining. The middle of August is the starting period for calculating the accumulative chloride concentration in the boundary layer, which is starting at 0 $kg/m^3$ of chloride concentration.

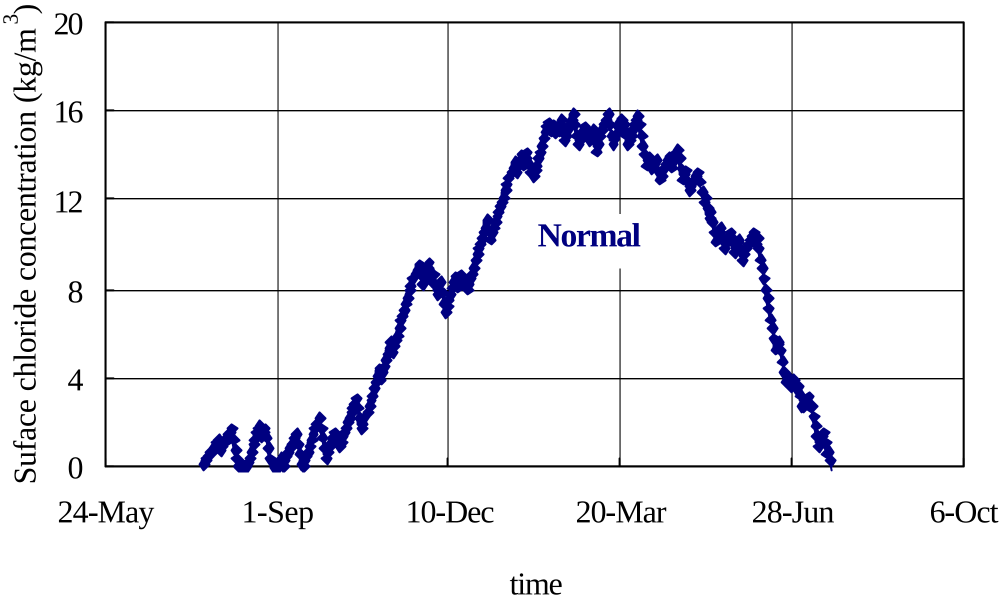



**Fig.5.4.3 (a):** The prediction of 1-year chloride concentration in normal condition of Kochi prefecture.

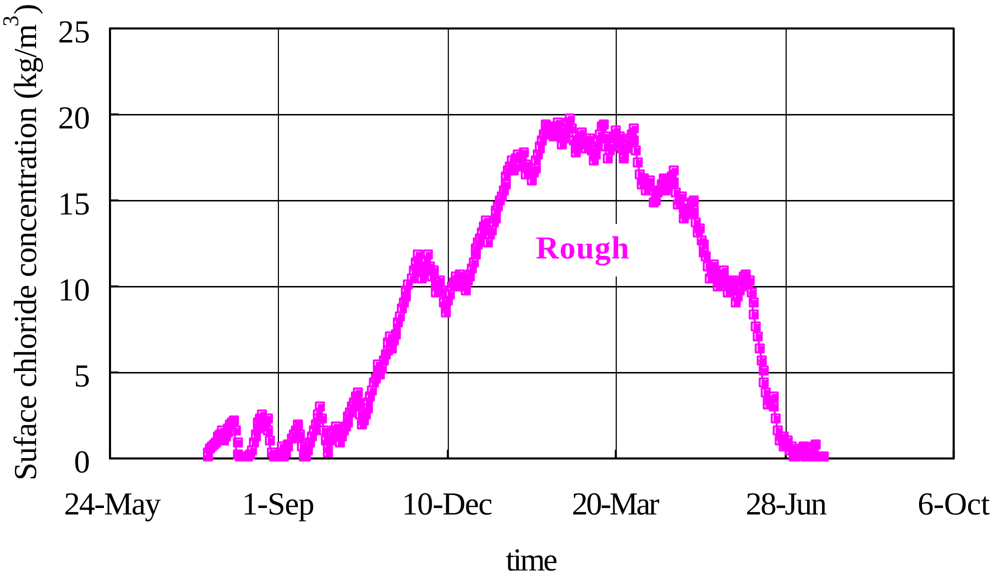



**Fig.5.4.3 (b):** The prediction of 1-year chloride concentration in rough condition of Kochi prefecture

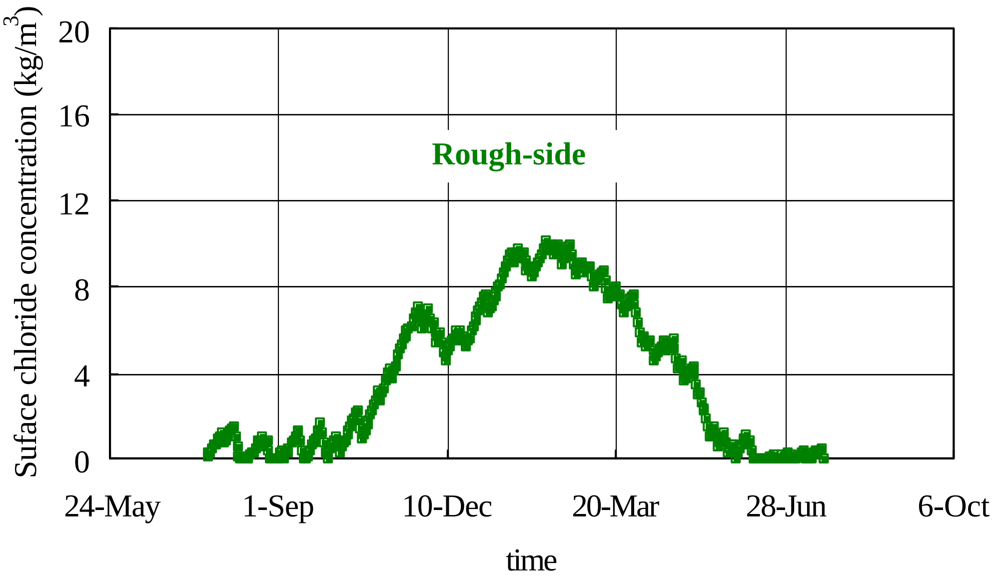



**Fig.5.4.3 (c):** The prediction of 1-year chloride concentration in rough surface with 90° perpendicular to seashore of Kochi prefecture

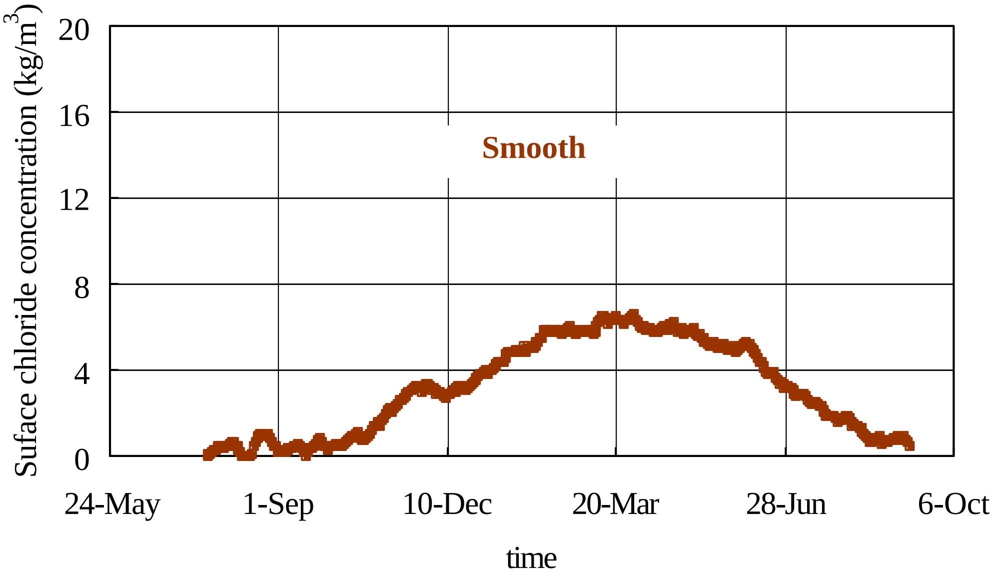



**Fig.5.4.3 (d):** The prediction of 1-year chloride concentration in smooth surface with 100% rain of Kochi prefecture

The predicted results are verified by the experimental data in **Fig.5.4.4**. The precision of high-accumulated chloride concentration is not good and error is large about 1 kg/m3. Although, the reason might be caused by the precision of model and the accuracy of experimental results, it may affect to a large deviation. In order to check the precision of the model the experimental work should do for whole year. However, the accuracy of this model can be verified again in final. This model is used as boundary condition for DuCOM simulation on chloride concentration in concrete. Finally, the verification is done again with the actual data from PWRI [12].

Later in Chapter 6, the monitoring of existing structures done by PWRI is discussed. In this section, the actual environmental effect of the monitored members is analyzed same as the procedure described in this chapter. The various shape of 1-year accumulated chloride concentration is known. Importantly, this model is able to explain why the chloride concentration in a seashore structure is very low.

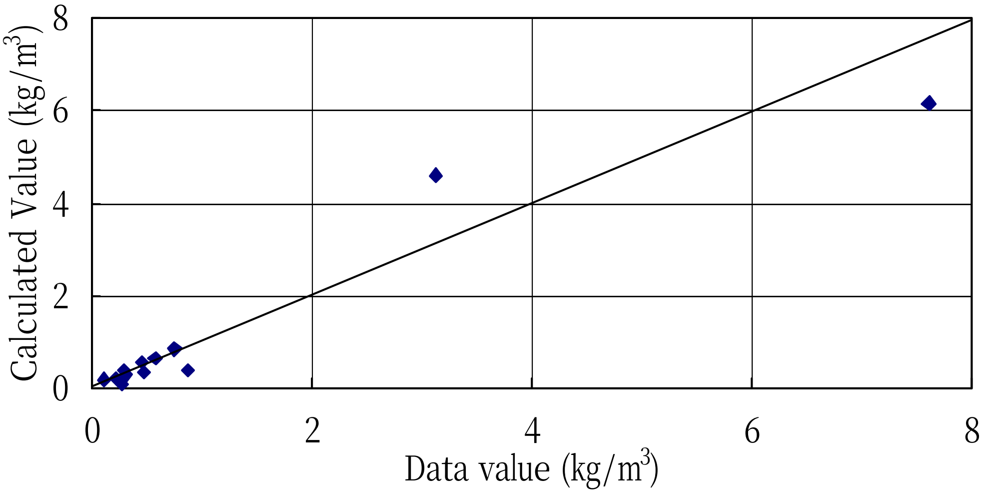



**Fig.5.4.4:** The verification of predicted accumulated chloride concentration with experimental results

## 5.5 The predicting standard accumulated chloride concentration around Japan

The prediction of the accumulated chloride concentration around Japan is very tough works, thus zoning of the similar severity is grouped into 4 zones as shown in **Fig. 4.3.10**. The standard environments representing the overall environment in a specific zone are selected as

**Zone 1:** Itokazu, Okinawa 2002

**Zone 2:** Otaru, Hokkaido 2002

**Zone 3:** Irozaki, Shizuoka 2002

**Zone 4:** Susa, Yamaguchi 2002

The environmental conditions in these 4 zones are analyzed as in Chapter 4 and shown in **Fig. 4.3.13**. The accumulated chloride concentration starts with the different month, because the model want to calculate the accumulated in 1 year iteration with starting and ending point in zero value. It is easier to use 1-year iteration of chloride accumulation for simulating the chloride transport in concrete by DuCOM. It helps the simplicity of the input data as 1-year iteration until the simulated life is achieved. The maximum value of chloride concentration and area under the graph between chloride concentration and time is highest in Okinawa area. The second severe location is in zone 2. For zone 3 and zone 4 has similar severity but the division was done according to the different of efficient wind direction. The predicted results were calculated under various conditions as mentions in **Table5.4.1**. The entire calculated results are illustrated in Appendix A. The seashore outer structures have higher severe condition in all 4 zones than those inner structures. The last figure of each zone is the accumulative at 1-year interval, and this chloride accumulation is multiplied by number of years for simulating at a considered age. The outer structures in later distance from coastline has a little chloride attack due to the raining effect is relatively larger than amount of adsorption. It might be said that the chloride attack on outer structure is controlled by rain and kept very low surface chloride concentration. In the opposite way, inner structures without wind effect still have large effect on accumulation.

# CHAPTER 6

# Verification of the computational model on chloride distribution

## 6.1 DuCOM modification

According to the computational program in simulating the chloride transport in concrete; the governing equations are described in the Chapter2. The flux movement in the surface layer of concrete is due to both diffusion and the condensation of chloride ions by ion adsorption [11,23]. Maruya, et al, proposes the surface chloride condensation as the quasi-adsorption as in function of chloride concentration at 1cm surface layer. However DuCOM is microstructure based simulation model, the boundary surface layer is small as the pore structure at surface. The condensation influences to the flux movement of free chlorides in surface pore structure. The flux due to quasi-adsorption in the computational program was modified as the function of free chloride at surface layer,

$$q_{ads} = 6.5x10^{-3} \exp(-1.15C_{cl}) \quad (6.1.1)$$

where: $q_{ads}$ is flux of quasi-adsorption (mol/cm$^2$/day)

$C_{cl}$ is free chloride content at boundary layer, (mol/l)

Referred to **Fig.6.1.1**, zone1 represents the ambient environment at outer surface of concrete, zone 2 is the surface layer due to depth of roughness, and zone 3 corresponds to the concrete structure. From previous study of submerged and wetting-drying cycles, the ambient environment is known as chloride concentration equaled to sea concentration about 3% NaCl. Nevertheless, the ambient environment of a structure in the atmosphere is unidentified. Thus the surface layer of zone2 is equivalent as the ambient environment of that concrete structure. So the input chloride concentration of ambient environment changes to use the free chloride concentration at surface layer in zone2, $C_{cl}$, instead. Consequently, the experiment of total chloride concentration at surface layer, $C_o$, [see Chapter5] is in unit of (kg/m$^3$). The conversion of the unit of mol per liter of pore volume is necessary. Moreover, the condensation term is included in the boundary condition already, thus it is abandoned. The adaptation of each time-dependence of total chloride concentration in concrete ($C_o$), to the free chloride in pore solution ($C_{cl}$) is computed by

$$C_{cl} = C_o\,(1-\alpha_{fixed}) \;.\; 1000 \;/\; [M_{cl}.V_{pore}.\; S] \qquad (6.1.2)$$

and,

$$\alpha_{fixed} = \begin{cases} 1.0 & C_{tot} \leq 0.1 \\ 1-0.35(C_{tot}-0.1)^{0.25} & 0.1 \leq C_{tot} \geq 3.0 \\ 0.543 & 3.0 \leq C_{tot} \end{cases} \qquad (6.1.3)$$

where, $C_{cl}$ is free chloride concentration at boundary layer (mol/l)

$C_o$ is total chloride concentration at surface (kg/m$^3$)

$C_{tot}$ is total chloride concentration (% by weight of cement)

is $[C_o\ .100\ /\ Wc]$

Wc is weight of cementitious material (kg/m$^3$)

$M_{cl}$ is molecular weight of chloride (35.5 g/mol)

$V_{pore}$ is pore volume (l/m$^3$) of a concrete (computed by DuCOM)

S is degree of saturation, [saturated condition is 1.0]

$\alpha_{fixed}$ is the ration of fixed chloride [Proposed by Maruya, et al,1992]

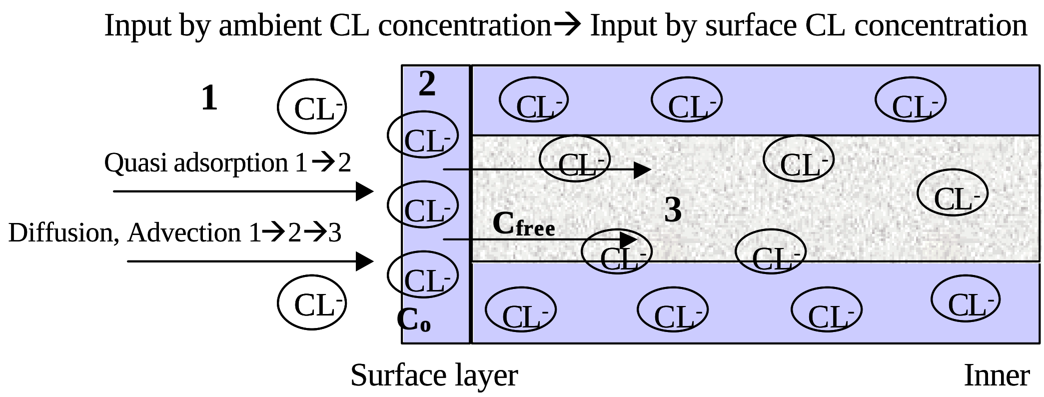



**Fig.6.1.1:** Condensation mechanism of chloride ions in the surface layer of concrete [23]

The pore solution and degree of saturation are obtained using the same computational program by applying the actual environmental condition. The pore structure and volume through the depth of concrete is assumed as a consistent distribution. The result of the available water in the pore system is used for calculating $C_{cl}$ (mol/l) at the surface layer. The flux of quasi-adsorption at the surface is ignored because none of the effect from the ambient environment. The flux of chloride ions at surface, $F_c$' was modified by

$$F_c' = -D_{cl}\,(C_{free}-C_{cl})/\Delta x \qquad (6.1.4)$$

where $D_{cl}$ is chloride ion diffusivity in pore solution phase ($m^2/s$),

$C_{free}$ is free chloride concentration in the pore solution on the inner surface of boundary layer [Between zone2 and zone3]

## 6.2 Sample calculation for verifying chloride distribution in concrete

The verification in this section used the investigated data as shown in Appendix B. The data was observed in various structures and locations totally 152 data, but only few of them have enough information in analysis. The exact location and distance, concrete property and types of structure by photographs are necessary information to judge the suitable condition for analysis referred to **Table 5.4.1**. According with the required information, the data is considered the appropriate circumstance for each as shown in **Table 6.2.1**. The investigated data of strength has to evaluate the water to cement ratio as input condition in DuCOM. The evaluate of the structure constructed since long time ago, the formula is proposed by Kokubu, 1950 [24]

$$f`_{c(28)} = -377+377c/w \qquad 6.2.1)$$

where, c/w is cement to water ratio

**Table 6.2.1:** Conditions in Simulation of each investigated data in **Appendix B**

| No. | Condition | Co accumulation ($kg/m^3$) | Rain effect ($kg/m^3$) | Note |
|---|---|---|---|---|
| A1017 | Smooth-normal 100% rain | 0.0109 | -0.3630 | Low efficient wind direction, Rain drainage path |
| B1013 | Smooth- no rain | 0.0020 | 0.0000 | Water drainage sometimes |
| B2009 | Rough-100% rain | 0.0175 | -0.6500 | |
| D2016 | Rough-100% rain | 0.0175 | -0.6500 | |
| D3008 | Smooth-no rain | 0.0020 | 0.0000 | No CL attack, CL initial = 0.03 $kg/m^3$ |
| G1026 | Smooth-100% rain | 0.0080 | -0.2760 | CL initial = 2.835 $kg/m^3$ |
| G3003 | Smooth-no rain | 0.0020 | 0.0000 | Narrow efficient wind direction |
| H2018 | Normal-100% rain | 0.0138 | -0.4500 | surface facing opposite to sea, CL initial = 1.8 $kg/m^3$ |
| H4017 | Normal-100% rain | 0.0138 | -0.4500 | CL initial = 1 $kg/m^3$ |
| K1005 | Smooth-no rain | 0.0020 | 0.0000 | |
| K2005 | Normal-100% rain | 0.0138 | -0.4500 | CL initial = 1.25 $kg/m^3$ |
| K3003 | Smooth-no rain | 0.0020 | 0.0000 | Low efficient wind direction |

The judgment on how to situate each data is the most important; however some unknown factors are assumed. For example, the surface in box culvert is affected in narrow wind direction. Wind direction in opposite to the surface in box culvert is thought as none of effect. Some indoor structures have to consider the drainage path, which can cause the rain effect whenever raining occurs. The surface roughness conditions in **Fig.5.2.1** are standard performance, and the extrapolation of roughness condition can be calculated as in data No.A1017. From the investigated results, the initial chloride concentration of each structure is unidentified. The calculated results of zero initial chloride contents in min and max curves are shown (Ex. B2009). Moreover, the result in the case that initial chloride concentration might exist shows the summation curve of the result with the estimated initial chloride concentration (Ex. G3003). The accumulated chloride for outdoor structure is using 1-year cyclic for whole life iteration (Ex. H4017). For indoor structures, the accumulated chlorides for entire life of that structure are necessary (Ex. K1005). Each investigated data is predicted the input data by **Eq.6.1.2**, and the calculation of total chloride concentration in concrete by DuCOM is compared with the investigated results as shown in **Fig.6.2.1-6.2.12**. It is noted that the accumulative value in each case is the total chloride concentration in $kg/m^3$. The conversion to the free chloride at surface layer is necessary for input in DuCOM. In fact, annual environments for whole life duration is not consistent, thus the cyclic of the accumulated chloride concentration is not alike. It is very hard work to create the exact input data, so the scattering of the environment in the average and the most severe weathers are needed to define as the multiplication factors. The distributions of weather condition and chloride concentration are a vital further study. In this verification, the iteration of 1-year accumulative chloride is applied as an average weather condition.

**Fig. 6.2.1: Verification of B2009**

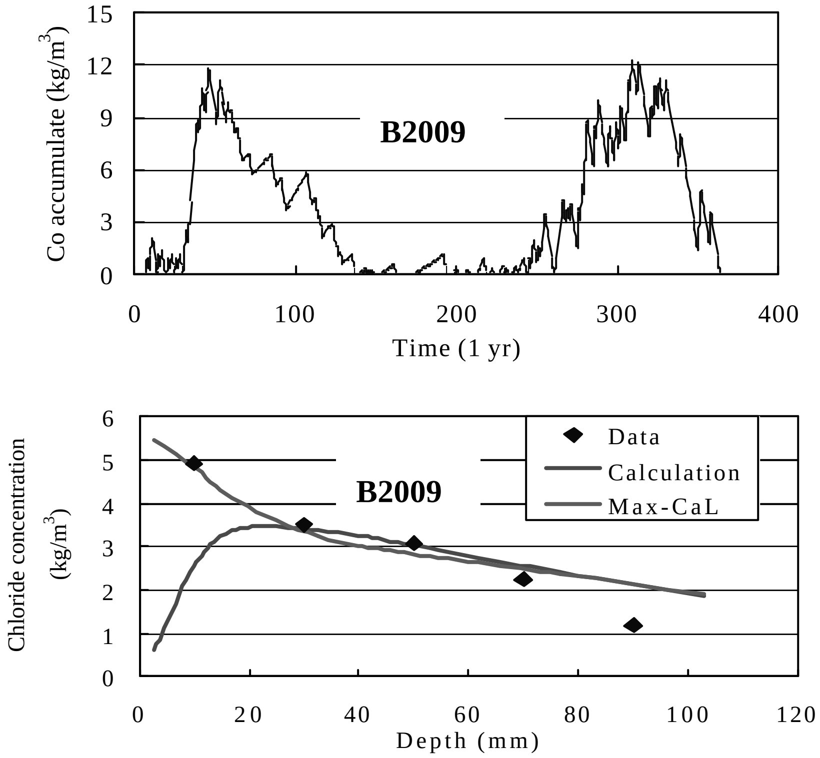



**Fig. 6.2.2: Verification of D2016**

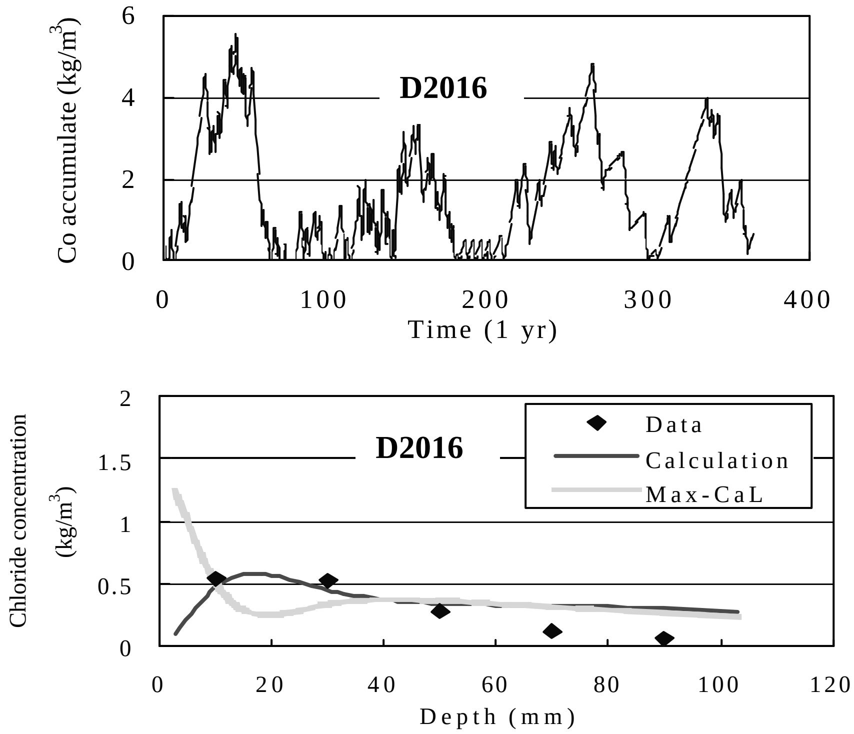


**Fig. 6.2.3: Verification of D3008**

# No Chloride accumulation at this location

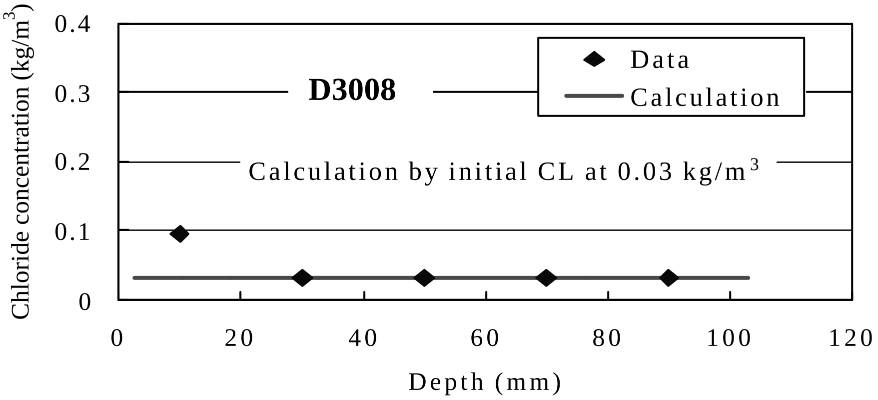



**Fig. 6.2.4: Verification of G1026**

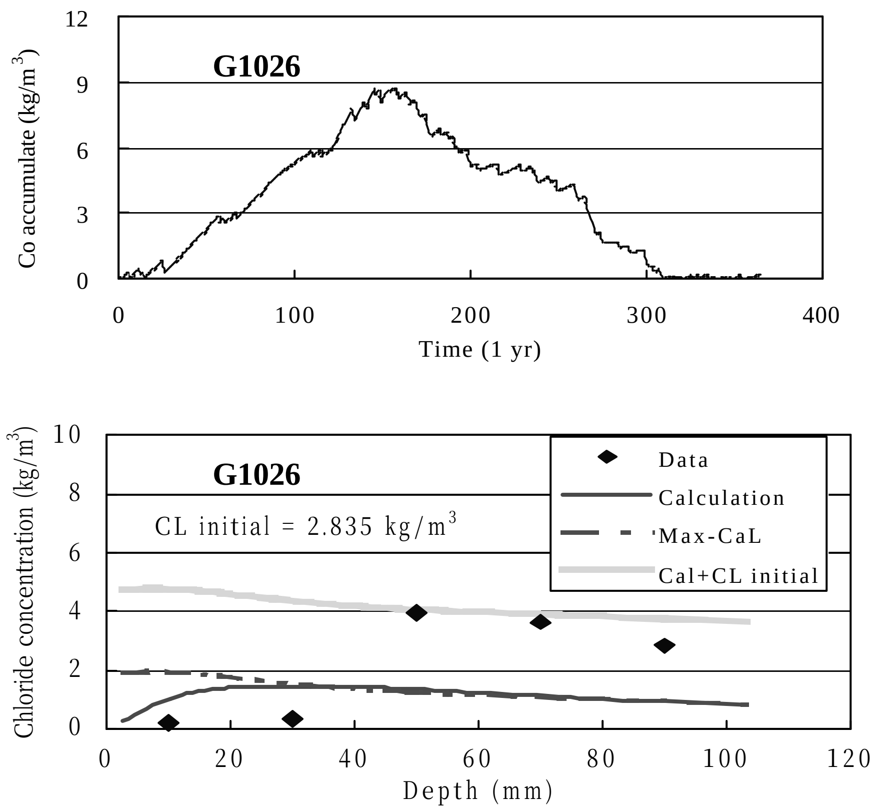
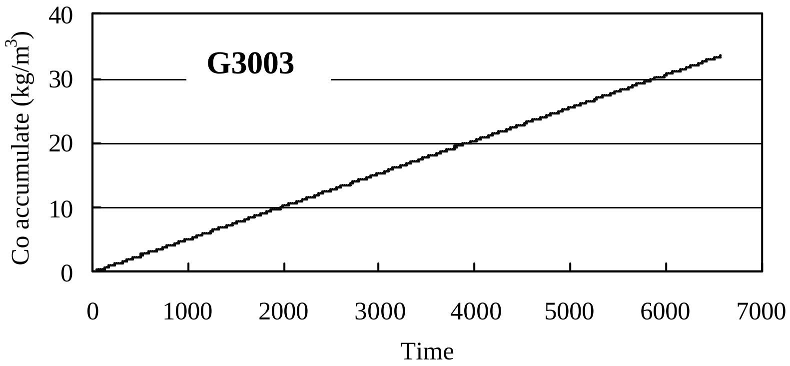


**Fig. 6.2.5: Verification of G3003**



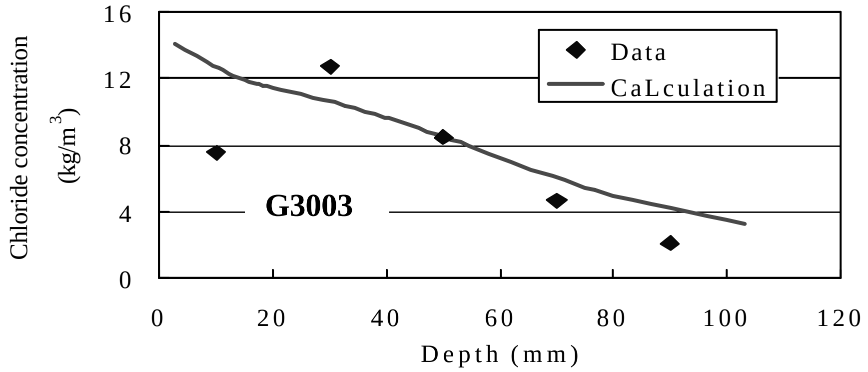
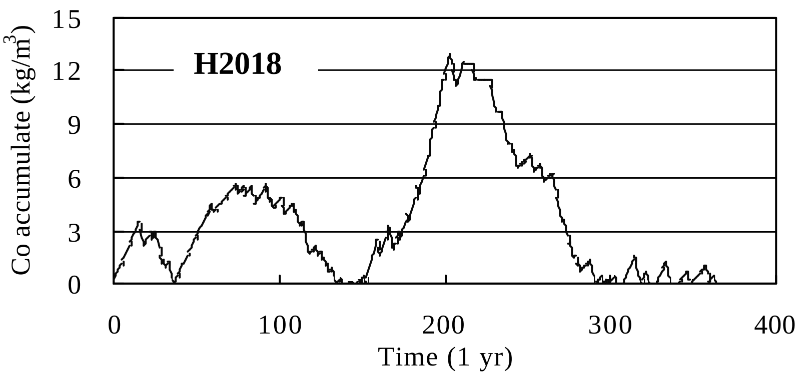




**Fig. 6.2.6: Verification of H2018**



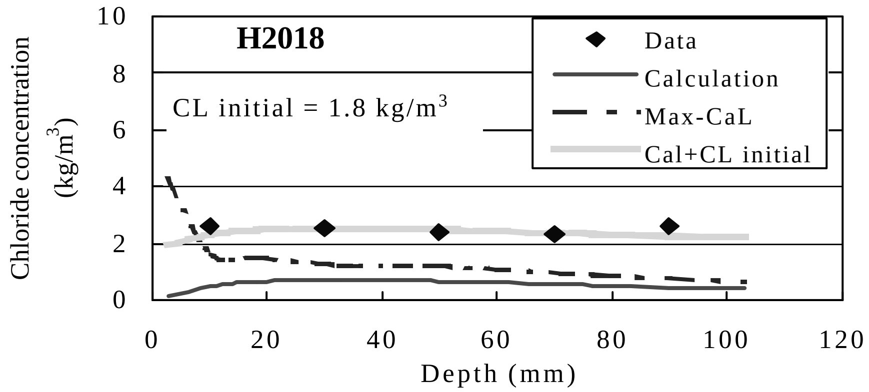



**Fig. 6.2.7: Verification of H4017**

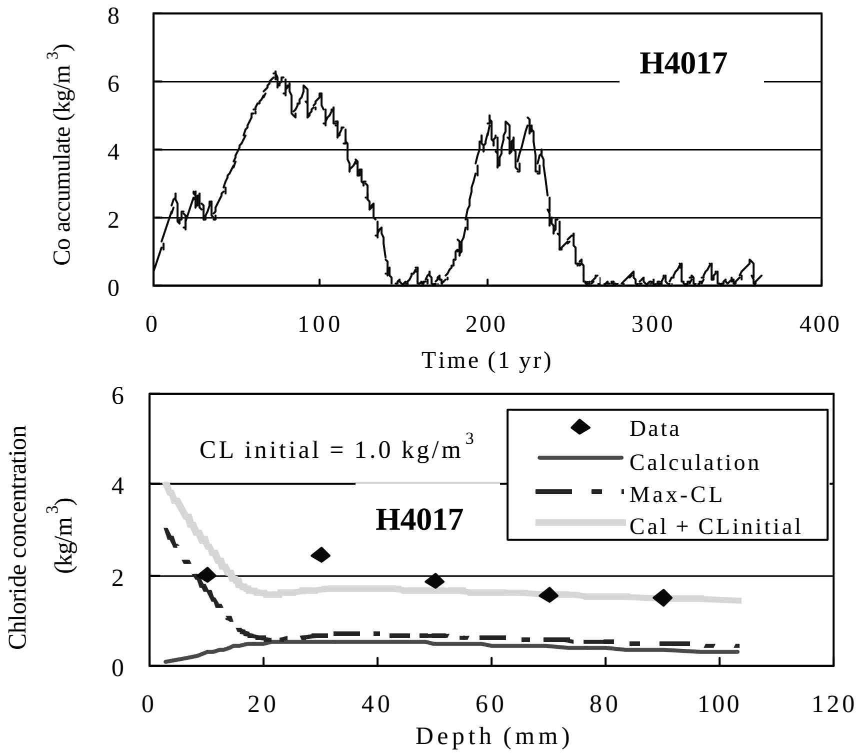



**Fig. 6.2.8: Verification of K1005**

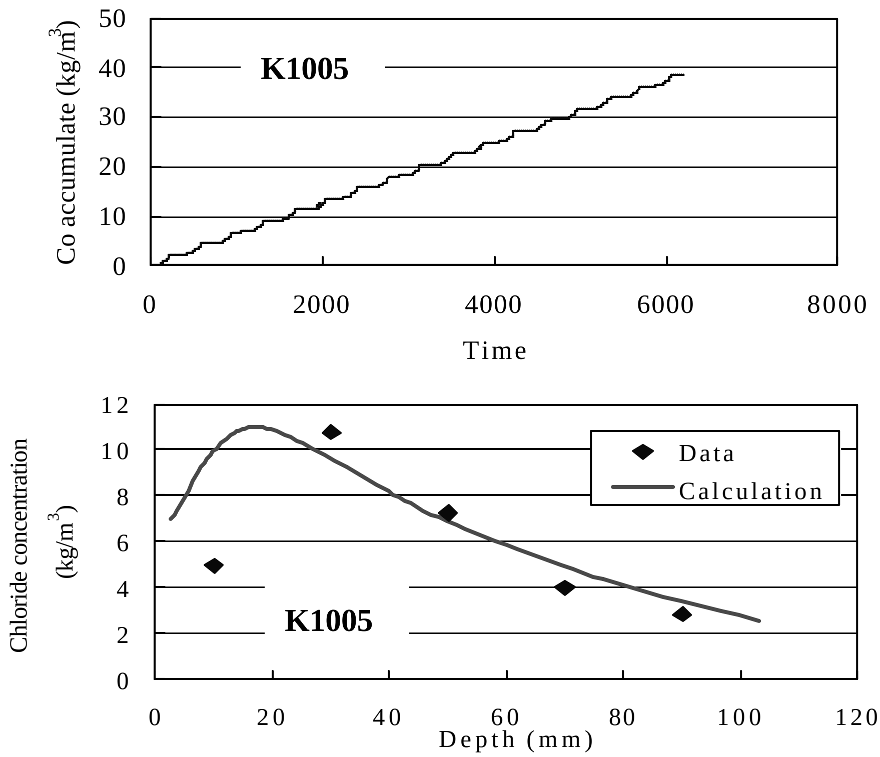


**Fig. 6.2.9: Verification of K2005**

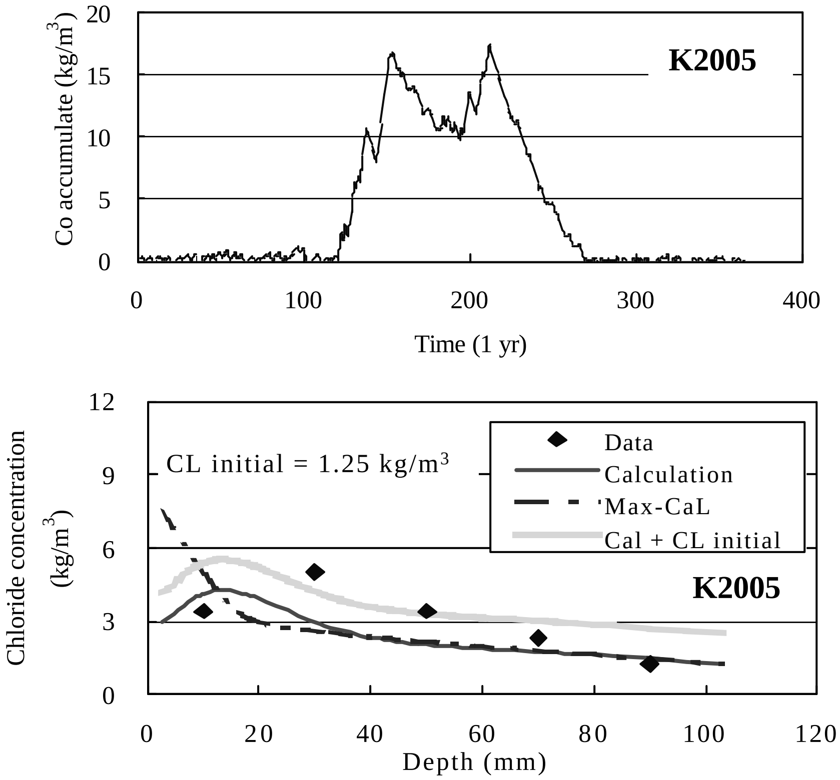



**Fig. 6.2.10: Verification of K3003**

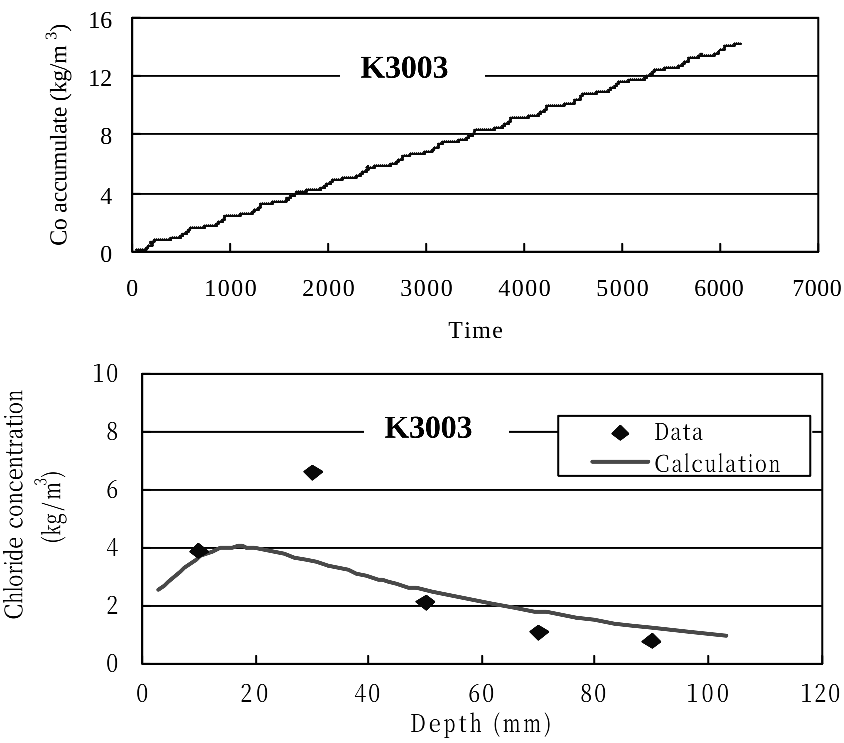


**Fig. 6.2.11: Verification of A1017**

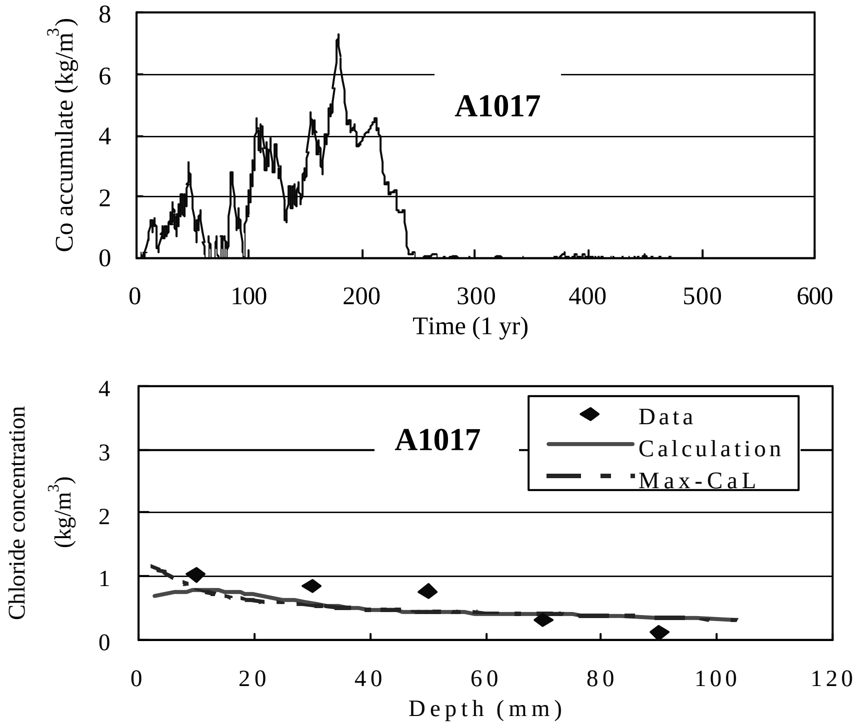
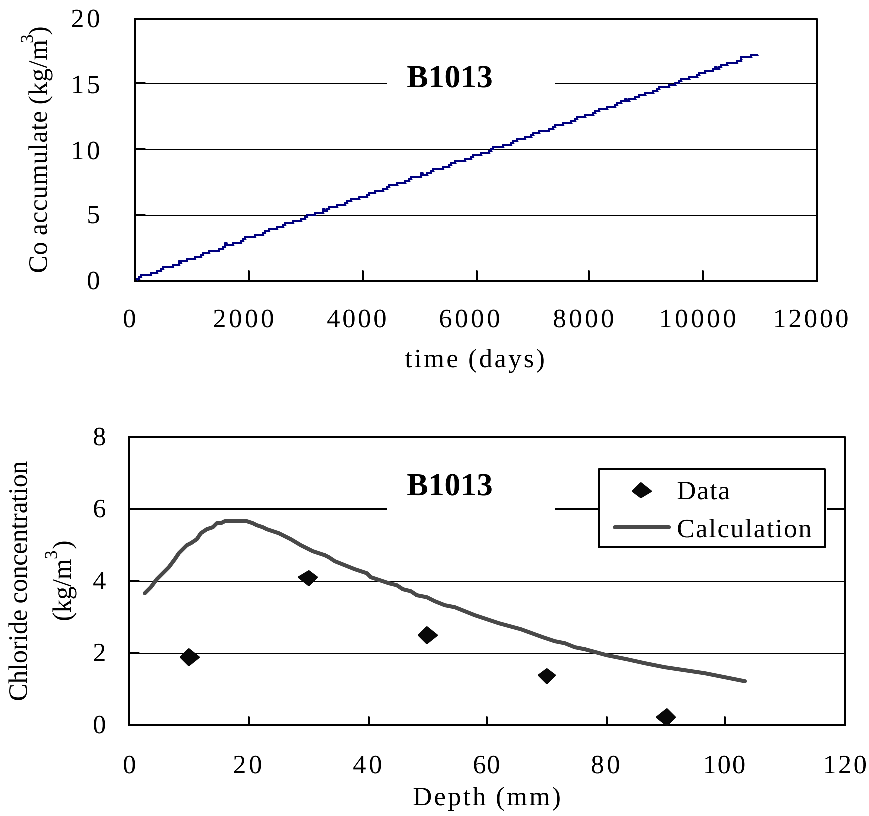



**Fig. 6.2.12: Verification of B1013**



The selected data in **Table 6.2.1** has been plotted the calculated chloride concentration in concrete at the depth of 1, 3, 5, 7, 9 cm. with the examined data. The comparison is plotted without the relationship of covering depth and shown in **Fig.6.2.13**. The least square of regression from this comparison is calculated at 0.723. The scattering of data occurs in the range of high chloride concentration where is taken from the depth near to surface. The depth of 0-3cm from surface of concrete subjecting to various environmental conditions such as wetting-drying cycles, carbonation and shrinkage crack is influenced from the fluctuation of chloride concentration with time history.

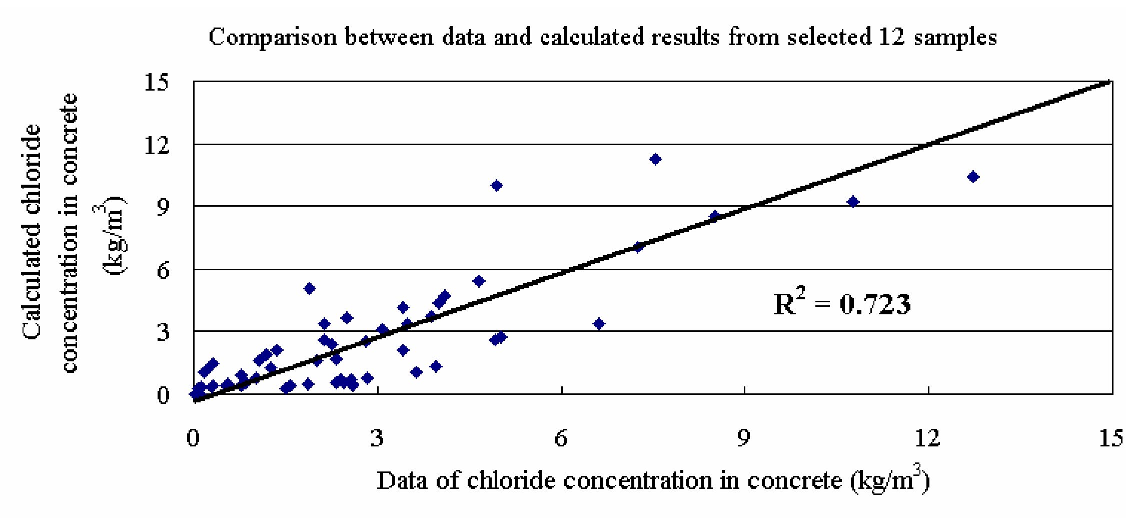



**Fig.6.2.13:** Comparison of chloride concentration in concrete in actual structures from 12 selected samples in **Table6.2.1**

# CHAPTER 7

# New proposed design method

## 7.1 Recent design

At present, the design of chloride concentration follows the evaluation method proposed by Japan Society of Engineers until year 2002 [25-26]. The chloride ion penetration can be calculated by Fick'2$^{nd}$ law as below,

$$\frac{\partial C}{\partial t} = Dc\left(\frac{\partial^2 C}{\partial x^2}\right) \quad (7\ 1.1)$$

where; C: is chloride ion concentration

$D_c$: is bulk diffusion coefficient

x: is penetration depth

t : is exposure time

The chloride ion concentration at reinforced steel position in concrete is computed by the modification of **Eq.7.1.1** to

$$C(x,t) = Co\left(1 - erf\ \frac{x}{2\sqrt{D.t}}\right) + C(x,0) \quad (7.1.2)$$

where, C(x,0) is the initial chloride ion concentration (kg/m$^3$)

D is apparent diffusion coefficient, cm$^2$/yr (For Ordinary Portland Cement, calculated by

$$\log D = -3.9(w/c)^2 + 7.2(w/c) - 2.5 \quad (7.1.3)$$

Co is chloride concentration at the surface (kg/m$^3$) [*See* in **Table 7.1.1**]

C(x,t) is chloride ion concentration at steel position (kg/m$^3$)

x is covering depth (cm)

**Table 7.1.1:** The chloride concentration at surface of concrete in a certain distance

| | Distance from seashore (km) | | | | | |
|---|---|---|---|---|---|---|
| $C_o$ | Splash | Seashore | 0.1 | 0.25 | 0.5 | 1 |
| ($kg/m^3$) | 13 | 9 | 4.5 | 3 | 2 | 1.5 |

First of all, the explanation of the specification of JSCE 2002 is needed to realize the current thoughts. The evaluation of chloride concentration at the position of reinforcing bars is based on the Fick'$2^{nd}$ law equation. There are 3 main dependent variables in the Fick'$2^{nd}$ law equation; chloride at the surface ($C_o$), apparent diffusion coefficient (D), service life (t). The $C_o$ is set as the function distance from sea by the longer distance from sea, the less $C_o$ is. The apparent diffusion coefficient (D) is computed by the equation with related to w/c. The equation is the average apparent diffusion coefficients from the observed data among submerge zone, tidal zone, splash zone and atmospheric zone as shown in **Fig.7.1.1**. This technique leads to high fluctuation of diffusion coefficient and meaningless in truthful behavior. In a distance, the constant surface chloride concentration was proposed, but the zoning separation due to severity level [1, 7] cannot explain by this specification. The safety factors in calculation of chloride transport were introduced for conservation in design. Firstly, the limitation of chloride concentration when corrosion started is used 1.2 $kg/m^3$. Actually, the chloride concentration for starting corrosion is between 1.2 – 2.4 $kg/m^3$. Secondly, the design apparent diffusion coefficient given by **Eq.7.1.3** needs a modification factor of 1.3 for upper member due to bleeding effect. Thirdly, the safety factor for scattering of surface chloride concentration in concrete is compensated by the factor of 1.3 times. The modification based on this proposed model in this paper is the criteria for high accuracy design. The advance and complicated method is not a suitable choice for creating new design.

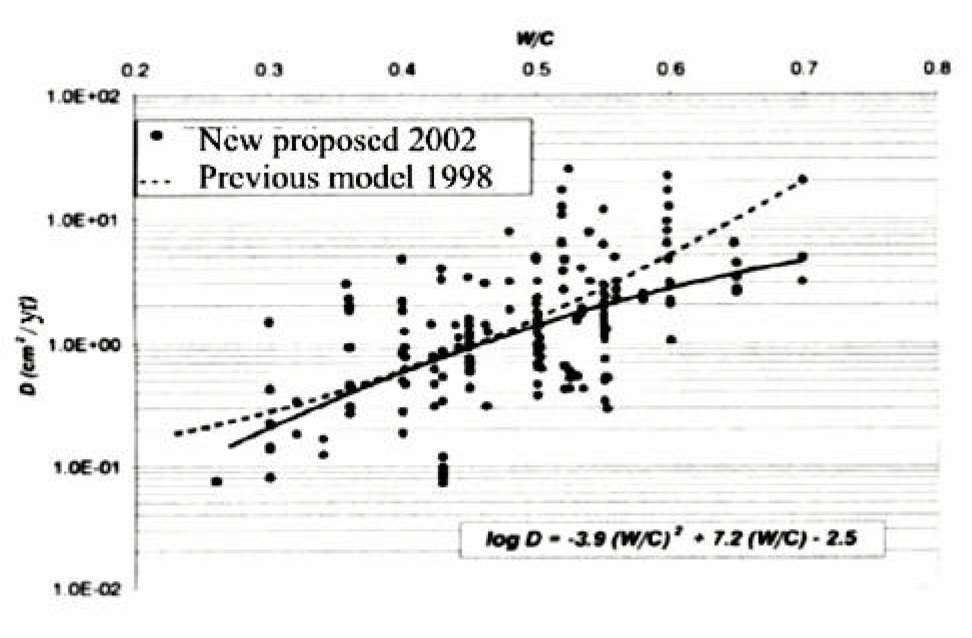



**Fig.7.1.1:** The apparent diffusion coefficient (cm²/yr)

## 7.2 New proposed design method

This new proposed design methodology is early-stated developed following the same conceptual design as current design. The improvement can be done by many means such as; redefine the parameters and the classification of each parameter. Referred to Fick' 2nd Law, the chloride concentration at surface of concrete is classified by zone, distance and structural conditions. Each parameter was considered on the mechanism and related artificial and environmental factors. The chloride concentration on the concrete surface changes dependently with weather condition in a specific region. In addition the surface of the structure itself has dissimilar degree of accumulation due to concrete roughness. Moreover, the distance from seashore is also the parameter, and the relationship is followed the model in **Chapter 4**. On the other hand, the chloride at surface of concrete is independent with the water to cement ratio.

The water to cement ratio is the factor that affects the diffusion behavior represented by diffusion coefficient. In previous calculation, the apparent diffusion coefficient is defined as material property and functioned with water to cement ratio only. However, collecting investigated diffusion coefficients from entire locations such as, tidal, splash and atmospheric zone used for the regression method. In fact, the diffusion coefficient should be considered with the difference of material usage only. The diffusion coefficient is set a standard condition under 91-days submerged condition in 3% of NaCl solution. The material is cast and cured under 28-days under water before exposure. The entire process keeps the temperature constant at 20°c. The calculating standard diffusion coefficient is achieved by using the computational program named DuCOM MC. After that, the application of the equation of Fick' 2$^{nd}$ Law is done for trial diffusion coefficient matching with the result. The standard diffusion coefficient of concrete using ordinary Portland cement, OPC can be shown as **Fig.7.2.1**. In usage of other cementitious materials, the experimental of the condition above is necessary for getting chloride concentration. Arrhenius's Law of diffusion represents the temperature influence on the rate of diffusion as shown below,

$$D_T = D_{20}.\exp[2285 \cdot (\frac{1}{293} - \frac{1}{(273+T)})] \qquad (7.2.1)$$

where, $D_T$ is diffusion coefficient at a certain temperature (cm$^2$/yr)

$D_{20}$ is diffusion coefficient at reference temperature of 20°c (cm$^2$/yr)

T is an average temperature (K)

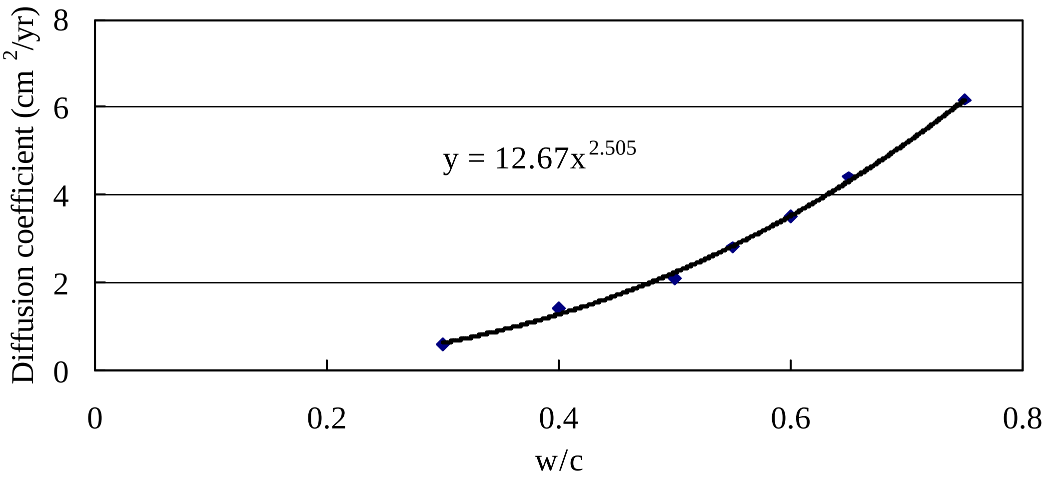



**Fig.7.2.1:** The diffusion coefficient in function of w/c [calculated by DuCOM]

Last, dependent parameter is service life span, the code was suggested this value as the design life of a structure, t. The new proposed time is the equivalent time, $t_{eq}$ due to the condition of exposure [change t → $t_{eq}$]. By Fick' 2nd Law, the standard diffusion coefficient of submerged condition is applied, thus the equivalent time means the time proportion to the time in submerged case. For example, the exposure time of concrete under various conditions, equivalent t is

$$\text{Submerged} \rightarrow t_{eq} = t$$
$$\text{Atmosphere} \rightarrow t_{eq} = t \,.\, f(r) \qquad (7.2.2)$$

where f(r) is reduction factor due to the ratio of diffusion duration. The diffusion duration is the equivalent of actual wetting-drying condition in each particular ambient environment. Thus f(r) is due to the level of RH inside concrete influenced by weather condition.

The **Fig. 7.2.2** shows the relationship between actual time and equivalent time. The actual environmental conditions depend on the diversity of climate around Japan. In the design, the concrete structures exposed into the environmental conditions are universally classified into outdoors and indoors. The difference of these two conditions is the raining affecting to removal of chloride concentration at surface of concrete and high wetting to drying ratio. The coefficient of f(r) for outdoor structures is lager than that for indoor structures according to the subjecting time of wetting state.

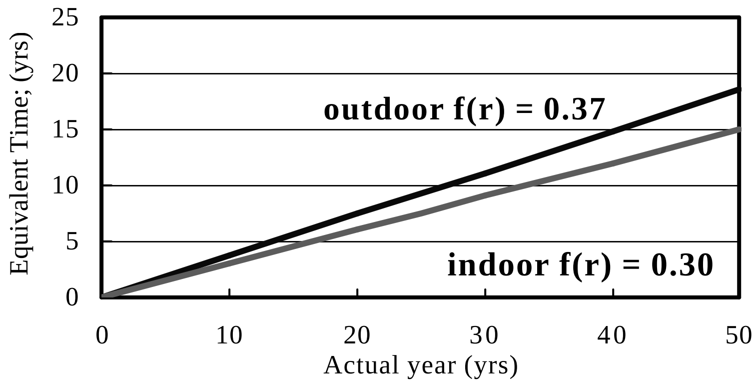



**Fig. 7.2.2:** Relationship between actual and equivalent time of exposure

Next the recommended value of chloride at surface of concrete is functioned with zoning, ambient environments, and distance. The equivalent surface chloride concentration ($C_{o,eq}$) is shown in **Table 7.2.1**. The equivalent surface chloride concentration is constant for any designed service life of a structure. The equivalent surface chloride concentrations of outside structures are very low in distance further than 100m in overall zones. In further distance from seashore, the chloride attack shows large effect only on indoor structures. The indoor structures have the increment of surface chloride concentration during exposure without the effect of rain taken into account.

**Table 7.2.1:** Surface chloride concentration of concrete in 4 zones

| Outdoor | $C_{o,eq}$ (kg/m$^3$) at seashore | | | |
|---|---|---|---|---|
| | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
| Rough 100% rain | **12.0** | **10.0** | **6.0** | **4.0** |
| Normal 100% rain | **11.0** | **8.0** | **4.5** | **3.0** |
| Smooth 100% rain | **7.0** | **4.0** | **3.0** | **2.0** |
| Smoooth 50% rain | **3.0** | **2.0** | **1.5** | **1.0** |

| Outdoor | $C_{o,eq}$ (kg/m$^3$) at 100m from seashore | | | |
|---|---|---|---|---|
| | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
| Rough 100% rain | **4.0** | **3.5** | **2.0** | **1.2** |
| Normal 100% rain | **3.5** | **3.0** | **1.5** | **1.0** |
| Smooth 100% rain | **2.0** | **1.5** | **1.0** | **0.8** |
| Smoooth 50% rain | **1.0** | **0.7** | **0.5** | **0.4** |

| Indoor | $C_{o,eq}$ (kg/m$^3$) | | | |
|---|---|---|---|---|
| | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
| Seashore | **20.0** | **18.0** | **14.0** | **10.0** |
| 100m | **15.0** | **14.0** | **9.0** | **5.0** |
| 500m | **7.0** | **6.0** | **3.0** | **1.5** |

The recommendation of equivalent chloride concentration on surface of concrete in this study shows in various zones (See **Fig. 4.3.10**), concrete surface conditions and exposed environments. The equivalent chloride concentrations in severe zones of zone 1&2 are larger than these in mild zones. Also, the values for indoor structures are very large comparing with the recommendation in JSCE specification. Although, the equivalent chloride concentration at surface of concrete is large, the equivalent time controls the rate of chlorides penetration. The calculations of time to corrosion in this method are less than the results by JSCE for all conditions in **Table7.2.1**.

Once the condition chloride concentration is known, the degree of scattering due to this analysis is decreasing. So, the recommended limitation of chloride concentration at steel position is able to use the average value of 1.2 to 2.4 $kg/m^3$ or 1.8 $kg/m^3$. At last, the design of a new concrete structure with required service life can be calculated by this means. Finally, the additional application of this model is able to predict the service life of existing structures whenever the investigation of a structure is examined. If the condition of covering depth, strength, surface condition and environmental attack were known, the current status and prediction of corrosion starting time are able to calculate. This is useful for the simulating existing structure and planning of future maintenance.

# CHAPTER 8

# Conclusion

The current circumstance of simulating chloride attack to concrete under actual environments is successfully by this computational model. The main criteria is to know 2 main factors of ambient airborne chlorides in the atmosphere and the accumulation on the surface of concrete under actual environments. Thus, the computational framework in order to make a model considering above two factors is necessary.

The computational model in this study has been proposed by categorizing into three sub-models integrating together. Three sub-models consisted of the airborne chlorides formation and transportation, the accumulation of airborne chlorides to the surface of the structure, and the chloride transportation into concrete. These integrated models considered from the source of airborne chlorides generation until obtaining the chloride concentration in concrete. Finally, the predicted chloride concentration in concrete is comparable with the investigated data from the existing structures.

Discussing the first sub-model, the sea wave produced airborne chlorides in the atmosphere is prior to consider. The airborne chlorides are formed after wave breaking by the concrete wall along seashore or wave bubble-crusting. The generated airborne chlorides fly in a specific height which depends on the residual of wave energy after wave breaking, natural or artificial offshore topography, and the horizontal wind speed. The amount of airborne chlorides after wave breaking is unknown; therefore the simple normal distribution is created as the representative values. The amount of airborne chlorides is transported along the distance from seashore by the horizontal wind. The transportation is based on the equilibrium of the gravitational settlement and the horizontal motion of each airborne particle size. The wind speed, particle size distribution and distance from seashore are known relating to the amount of airborne chlorides. After all, the verification of the model is done by comparing with the investigated data of monthly accumulative airborne chlorides from Public Work Research Institute.

Next, the airborne chlorides transport to the surface of structures. The model is the computation of accumulative chloride concentration at the surface of concrete. The surface of concrete is the boundary layer in the depth of 0-1mm from surface. The depth of the boundary layer is different due to the roughness of surface. The accumulative chloride concentration in the boundary layer is considered with the actual environments of wind, rain, surface roughness and amount of airborne chlorides. The removal of chloride concentration in the boundary layer is affected by rainfall for the outdoor structures. During rainy season, the dissolution of chloride concentration out of the surface of concrete is significant. Thus the amount of accumulative airborne chloride for outdoor structures is less than that in the indoor structures for long term accumulation. The structure located near seashore, although the raining duration is large, can have very low amount of chloride concentration in concrete. The advantage of this model is the ability to calculate the time dependent accumulative chloride concentration in the boundary layer, if the actual environmental conditions of wind speed, wind directions and raining period are known. The investigation of the chloride concentration at the boundary layer in Kochi prefecture is done for approval the calculation in this sub-model.

Come to the third sub-model, the DuCOM is the program used to calculate the chloride concentration in concrete if the accumulative chloride concentration, humidity, and temperature at the boundary layer are known. The combination of above two models is applicable to create the input data of accumulative chloride concentration at the boundary layer with time dependence for DuCOM simulation. In this section, the verification of the investigated chloride concentration in the existing structures is compared with the results from DuCOM simulation. The input data is created individually with the environmental conditions at the existing structural location from the investigated data by PWRI. The verification of the integrated model with the investigated data of actual structure is succeeded.

Finally, the successive integrated computational model in this study is able to simulate the chloride concentration in concrete under the actual environmental conditions. In various environmental conditions around Japan, the simulation can explain the level of severity of chloride attack to the concrete structures following the concept of this study. The knowledge of this research is modified the current design code in order to reduce the local of safety factor due to the accuracy improvement. At last, the modification of the current design code is proposed and the parameters are recommended from the calculation using this model. However, the approval of the high accuracy on the details of the formula in this study is necessary for further study.

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# List of parameters

$C_{air}$: daily average airborne chlorides (mg/dm$^2$/day)
CL: collected airborne chloride (mg/ml)
W: amount of water used for washing out from steel plate (ml)
t: exposure time (days)
A: specific surface area (= 1dm$^2$)
$C_{o,air}$: daily average of airborne chlorides at seashore (mg/dm$^2$/day)
*l*: distance from seashore (m)
$C_{air,1}$: airborne chlorides at 1 km from seashore (mg/dm$^2$/day)
$\lambda$: a multiplication factor
U: wind speed (m/s)
r: wind ratio in landward direction
R: regression value
$\phi$: porosity
S: degree of saturation
$C_{cl}$: free chloride concentration in pore solution (mol/l)
$J_{cl}$: flux of chloride ion (mol/m$^2$.s)
$Q_{cl}$: reduction of free chloride
$D_{cl}$: chloride ion diffusivity in pore solution phase (m$^2$/s),
$\Omega$: tortuosity of pore as equal to $(\pi/2)^2$
$C_{(x,t)}$: chloride ions concentration at time t (kg/m$^3$)
$C_o$: chloride ions concentration at surface of concrete (kg/m$^3$)
x: covering depth (cm)
D: apparent diffusion coefficient (cm$^2$/yr)
$t_{eq}$: equivalent exposure time (yrs)
$C_{(x,o)}$: initial chloride ions concentration (kg/m$^3$)
$\rho_{sea}$ : the density of seawater (kg/m$^3$)
E: wave energy density
$h_{wave}$: significant mean wave height (m)
g: gravitational acceleration (m/s$^2$)
h: height from datum base (m)
$\beta$: the modification factor due to wave energy
$\alpha$: the modification factor due to wind speed
$\rho_s$: density of particles (kg/m$^3$)

$\rho_{air}$: density of air (kg/m$^3$) at 1 atm
W: weight of an airborne particle (N)
$N_{uptrust}$ up trust force of an airborne particle (N)
$N_{drag:}$ drag force of an airborne particle (N)
$C_d$: coefficient of drag
$A_b$: projected area ($\pi d^2/4$), m$^2$
v: constant dropping speed (m/s)
d: airborne particle diameter (m)
$\mu_{air}$: dynamic viscosity of air (Ns/m$^2$)
Re: Reynolds' Number
X: distance of effective wind (m)
$W_{peak}$: peak weight of airborne chloride at U (mg/dm$^2$/hr)
$W_{peak(2m/s)}$: peak weight of airborne chloride at U=2 m/s (mg/dm$^2$/hr)
$\sigma_i$: standard deviation at U ((μm)
$\sigma_{(2m/s)}$: standard deviation at U = 2 m/s (μm)
$d_{i,max}$: maximum airborne particle size at seashore at a particular U
$d_{2,max}$: maximum airborne particle size at seashore at U = 2m/s
X': horizontal distance in an efficient wind speed (m)
$\varphi$: angle of an efficient wind to effective wind direction
$U_{eff}$: monthly effective wind speed with equivalent airborne chloride (m/s)
$\Sigma U_e$: monthly summation of wind only in the efficient wind direction (m/s)
$\Sigma r_e$: monthly summation of efficient wind direction (hrs)
$C'_{air,hr}$: modified airborne chloride after obstruction (mg/dm$^2$/hr)
$C_{air,hr}$: free transport airborne chloride in Table 4.3.1 (mg/dm$^2$/hr)
R(d): apparent reduction factor due to obstacle
$\Delta C_{o,i}$: coefficient of increasing surface chloride concentration at wind speed U
$\Delta C_{o,(3m/s)}$: coefficient of increasing surface chloride concentration at wind speed 3m/s
$q_{ads}$: flux of quasi-adsorption (mol/cm$^2$/day)
$C_{tot}$: total chloride concentration at surface (kg/m$^3$)
$C'_{tot}$: total chloride concentration (% by weight of cement)
$W_c$: weight of cementitious material (kg/m$^3$)
$M_{cl}$: molecular weight of chloride (35.5 g/mol)
$V_{pore}$: pore volume (l/m$^3$) of a concrete (computed by DuCOM)
$\alpha_{fixed}$: the ration of fixed chloride
$C_{free}$: free chloride concentration on the inner surface of boundary layer
c/w: cement to water ratio

$C$: chloride ion concentration

$Dc$: bulk diffusion coefficient

$D_T$: diffusion coefficient at a certain temperature ($cm^2/yr$)

$D_{20}$: diffusion coefficient at reference temperature of 20°c ($cm^2/yr$)

$T$: an average temperature (K)

$f(r)$: reduction factor due to the ratio of diffusion duration

$C_{o,eq}$: equivalent surface chloride concentration ($kg/m^3$)

$\Delta C_{o,x}$ : coefficient of accumulative surface chloride concentration at a distance

$\Delta C_{o,(30m)}$: coefficient of accumulative surface chloride concentration at 30m from concrete wave breaking

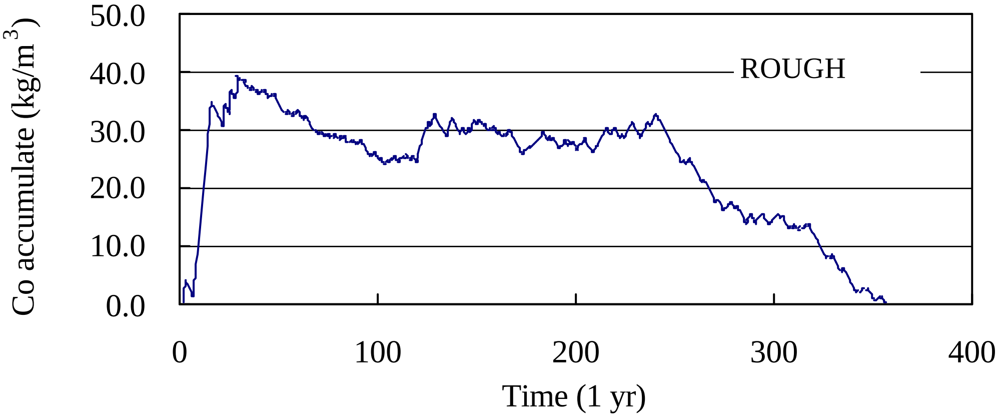
$C_{air,x}$ : amount of airborne chlorides at a distance

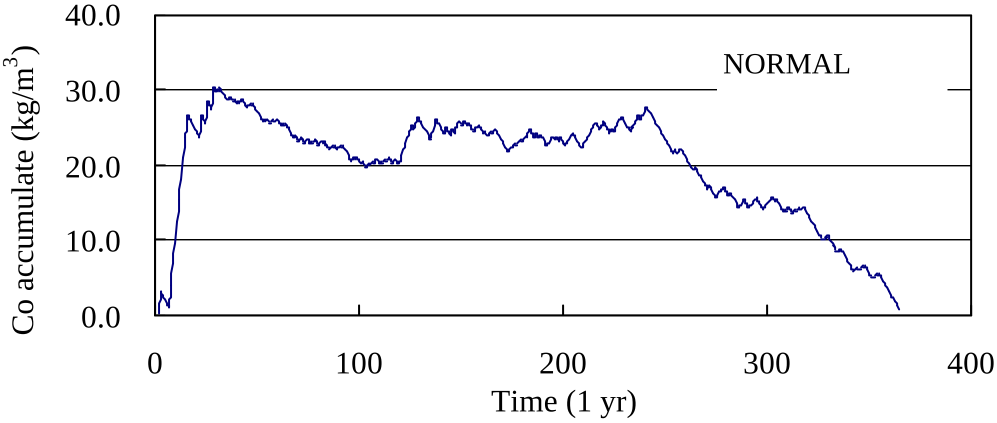
$C_{air,30m}$: the reference of the amount of airborne chloride at 30m from concrete wave breaking

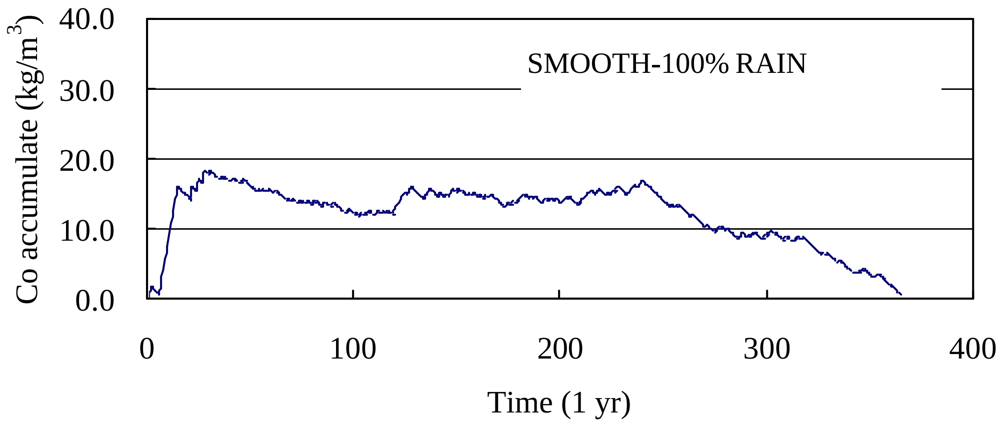
# Appendix A

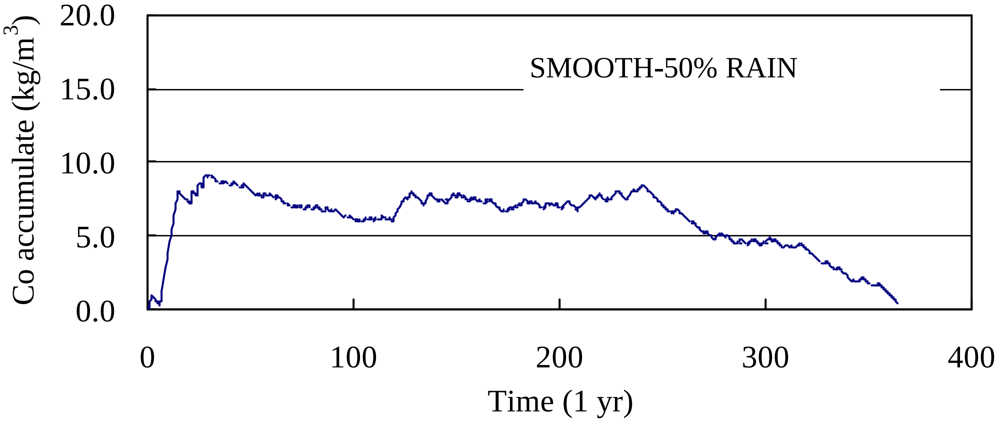
# Predicting results of accumulated chloride concentration in various zones

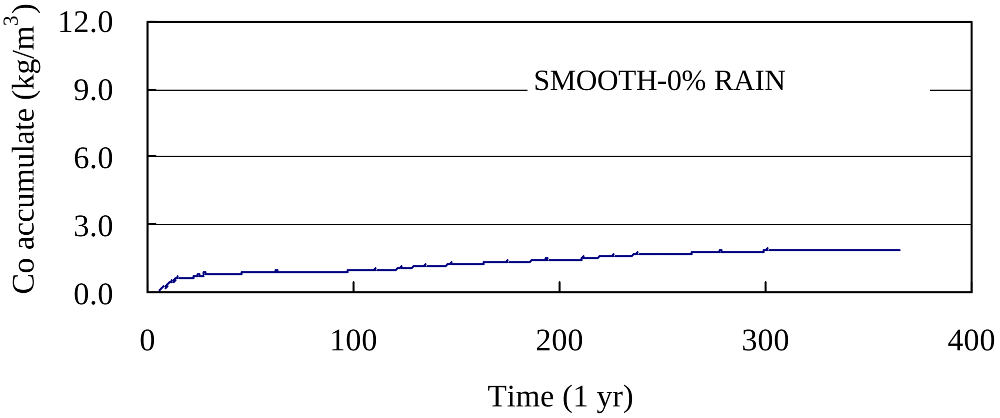
**Zone 1: At coastline in Okinawa**



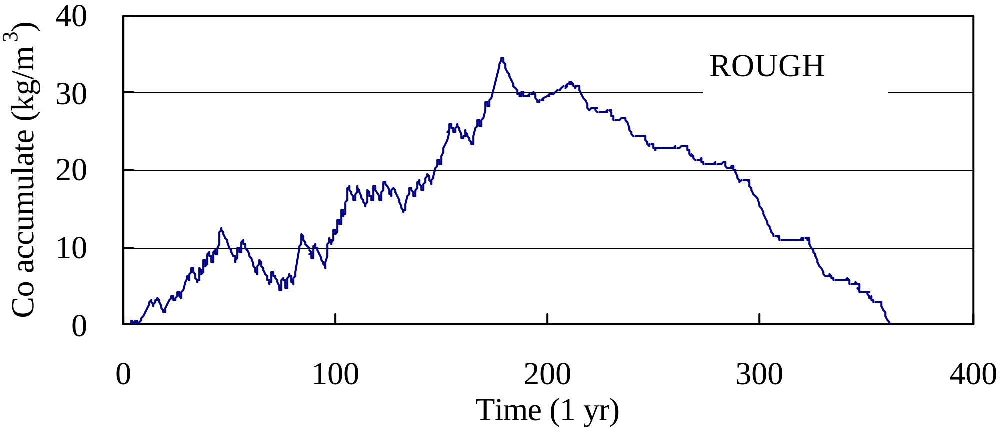



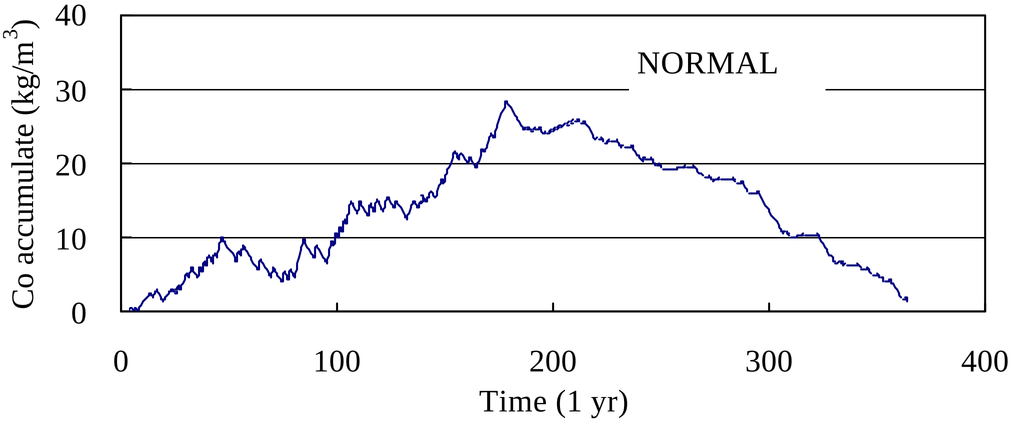



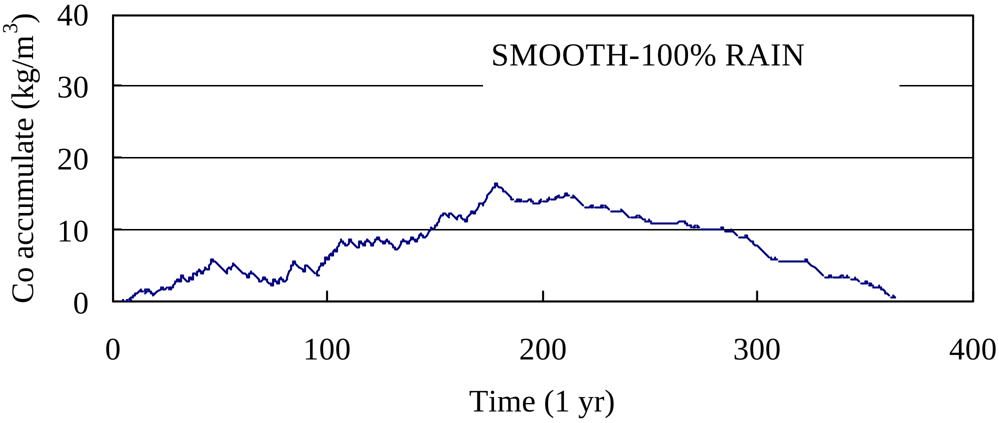

SMOOTH-50% RAIN
Co accumulate (kg/m3)
20.0
15.0
10.0
5.0
0.0
0
100
200
300
400
Time (1 yr)

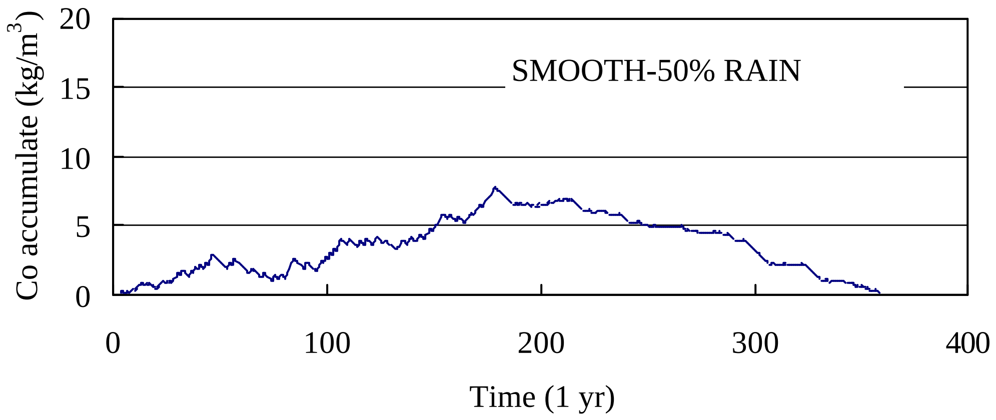

SMOOTH-0% RAIN
Co accumulate (kg/m3)
12.0
9.0
6.0
3.0
0.0
0
100
200
300
400
Time (1 yr)

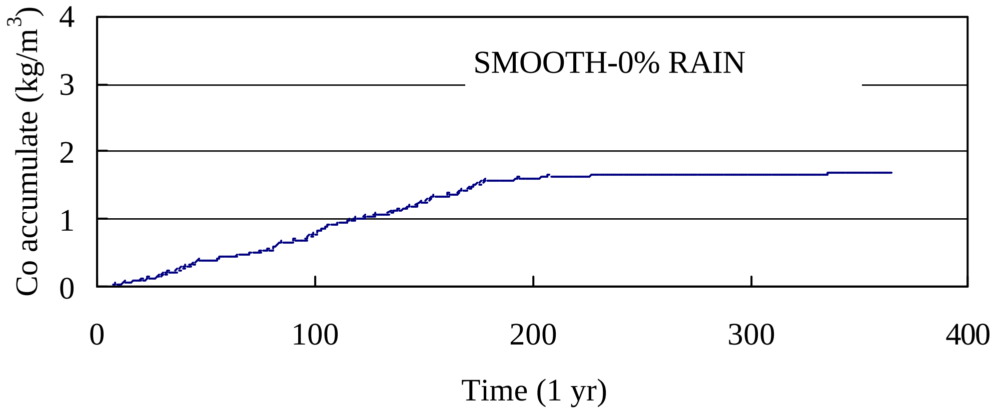
## Zone 2: At coastline in Japan Sea Coastline



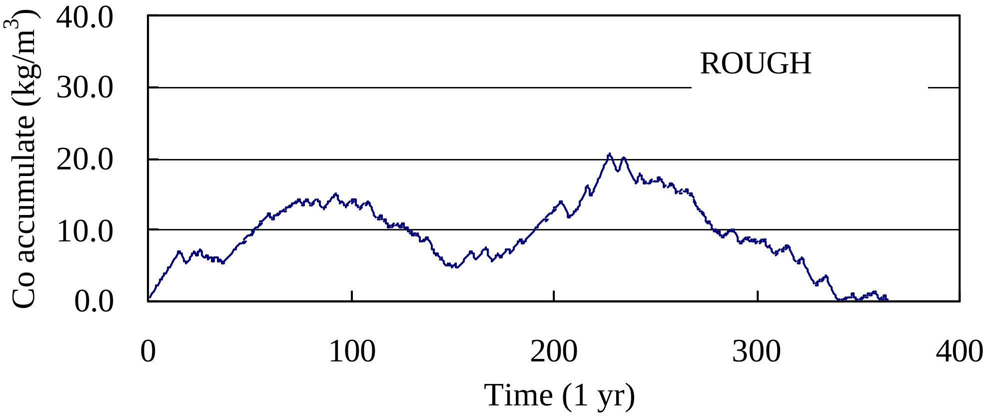



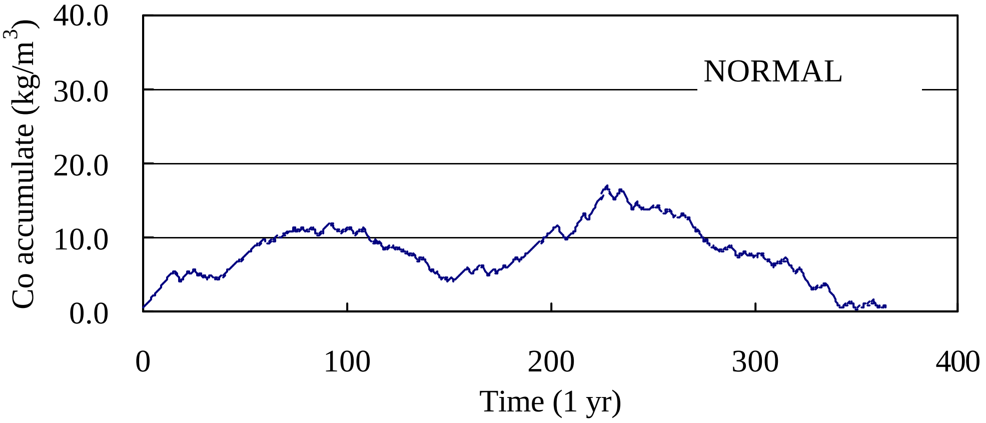



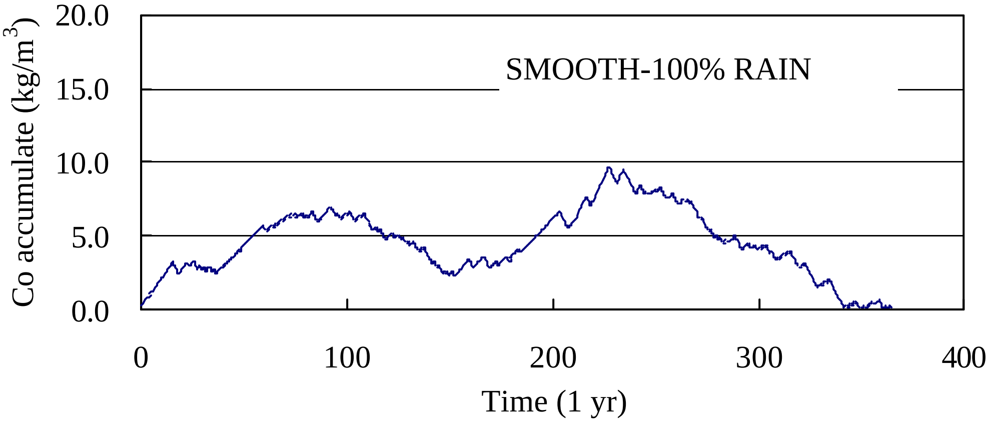

SMOOTH-50% RAIN
Co accumulate (kg/m3)
20
15
10
5
0
0
100
200
300
400
Time (1 yr)

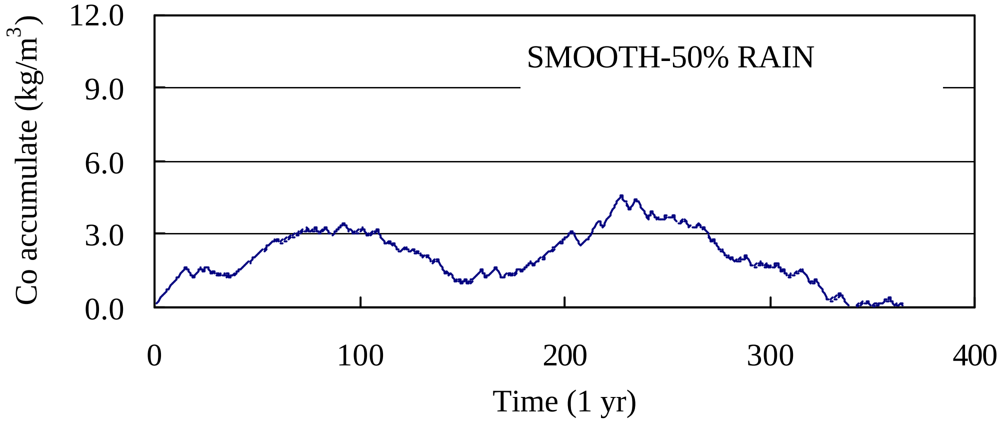

SMOOTH-0% RAIN
Co accumulate (kg/m3)
4
3
2
1
0
0
100
200
300
400
Time (1 yr)

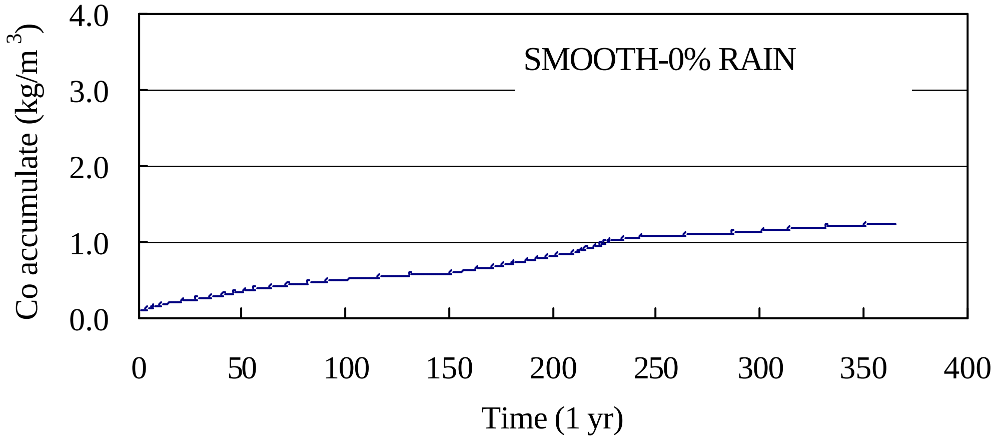
**Zone 3: At coastline in Pacific Ocean Coastline**



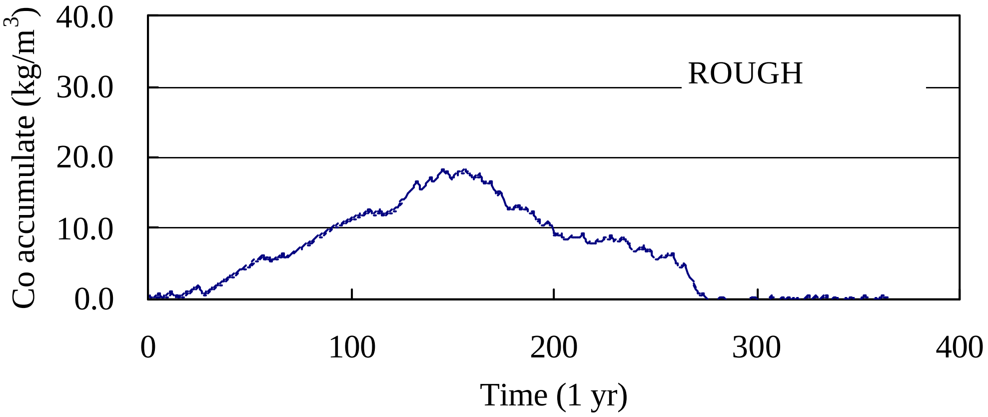



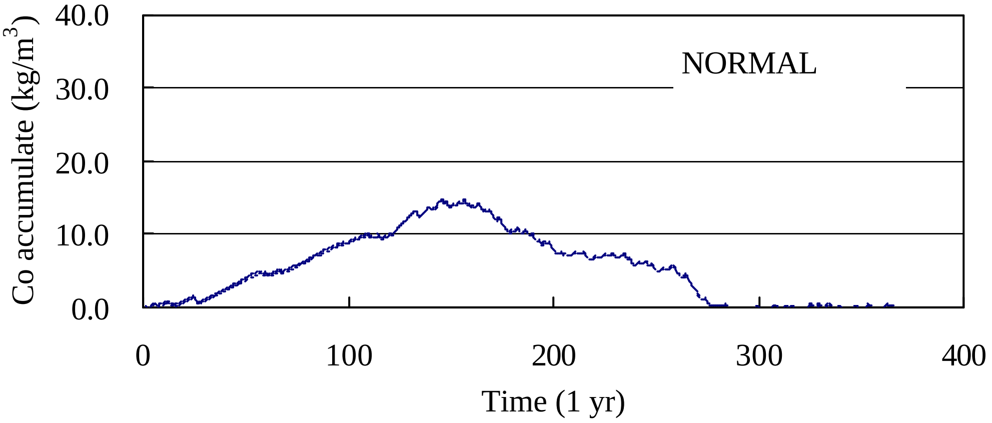



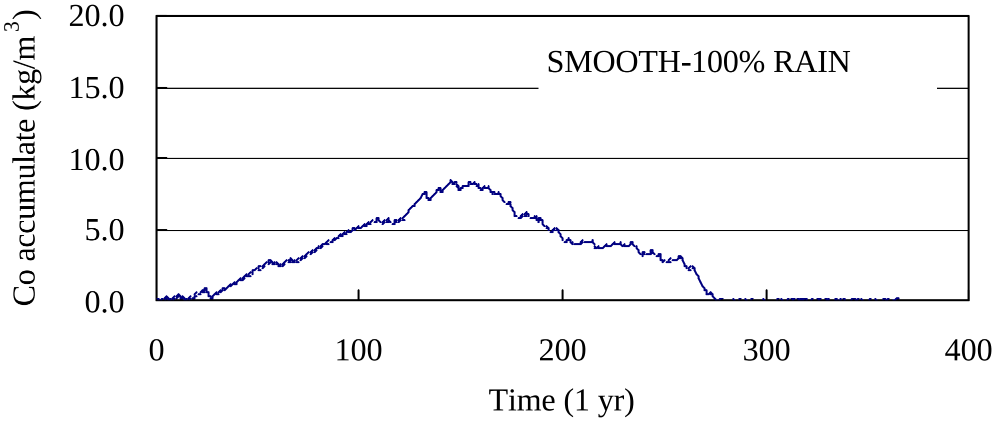

SMOOTH-50% RAIN
Co accumulate (kg/m3)
12.0
9.0
6.0
3.0
0.0
0
100
200
300
400
Time (1 yr)

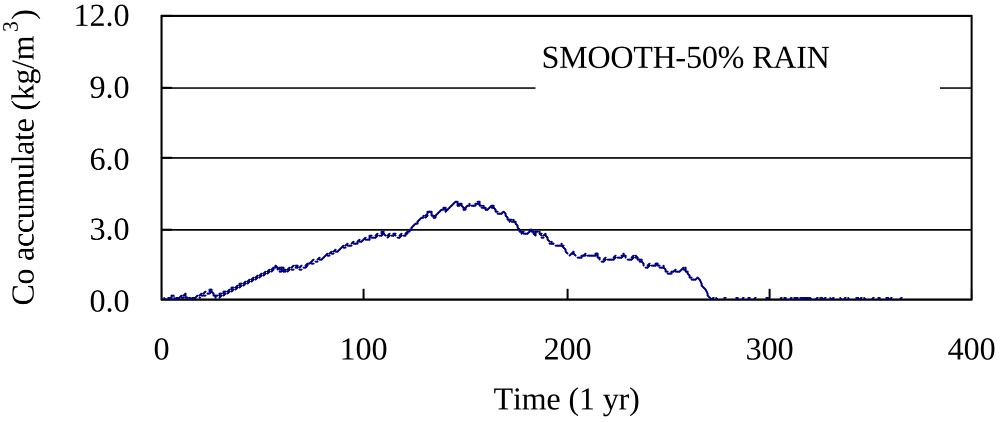

SMOOTH-0% RAIN
Co accumulate (kg/m3)
4.0
3.0
2.0
1.0
0.0
0
50
100
150
200
250
300
350
400
Time (1 yr)

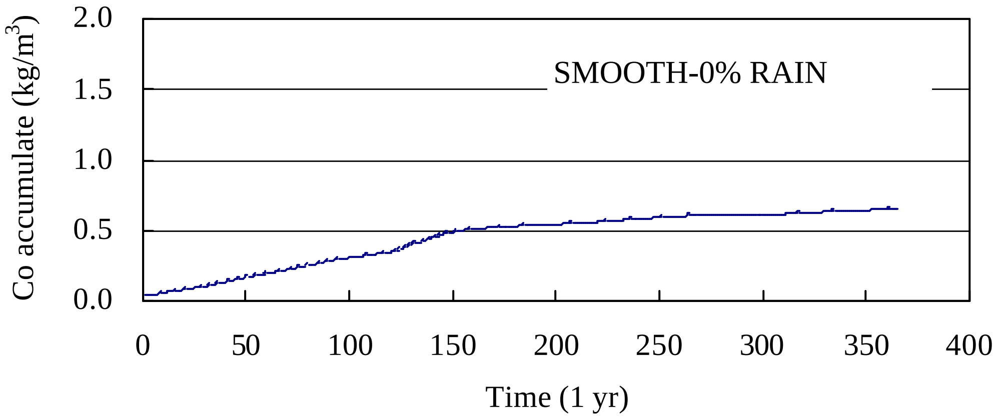
**Zone 4: At coastline in Chuubu to Nagasaki**



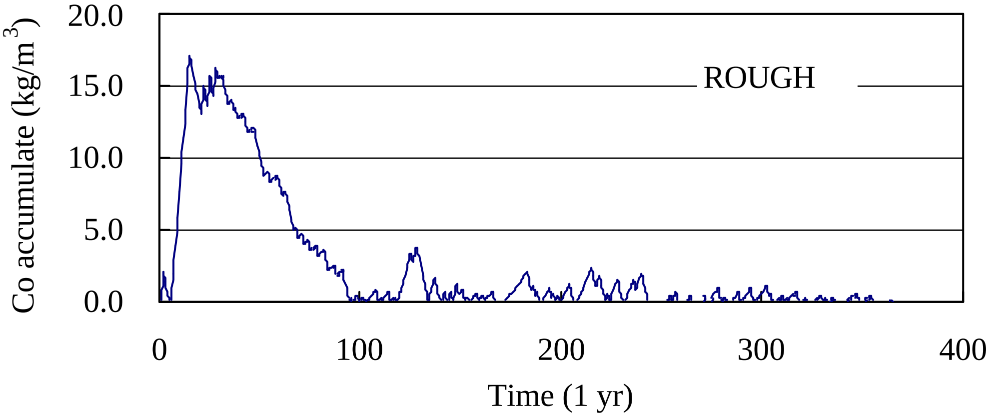



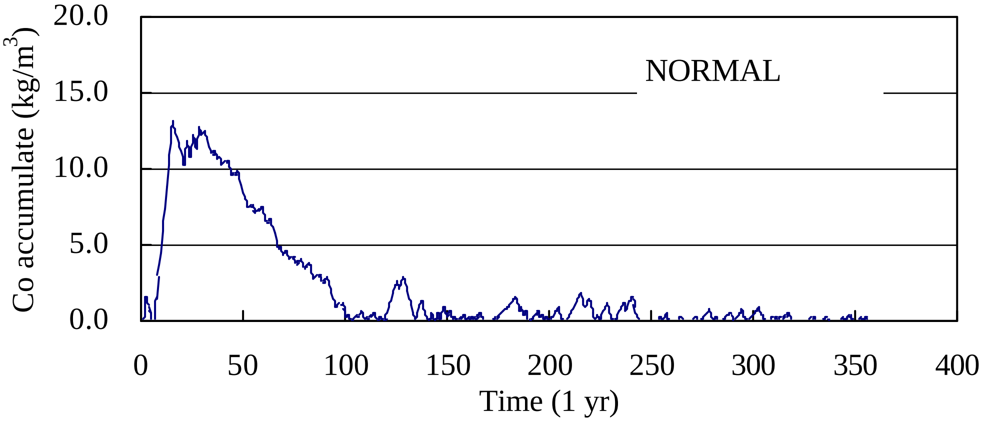



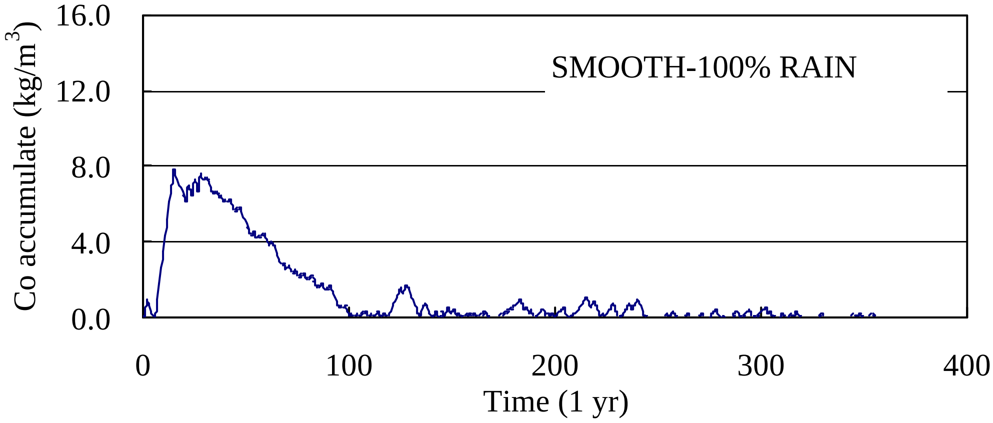

SMOOTH-50% RAIN
Co accumulate (kg/m 3 )
12.0
9.0
6.0
3.0
0.0
0
100
200
300
400
Time (1 yr)

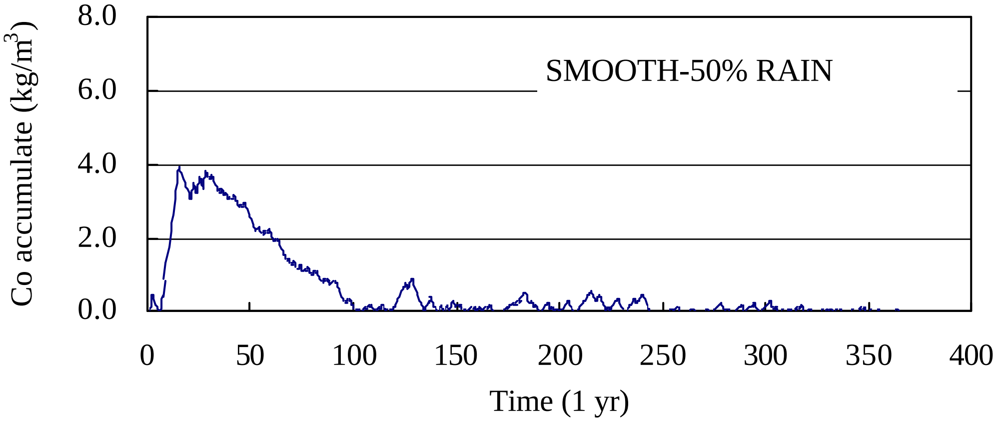

SMOOTH-0% RAIN
Co accumulate (kg/m3)
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
300
350
400
Time (1 yr)

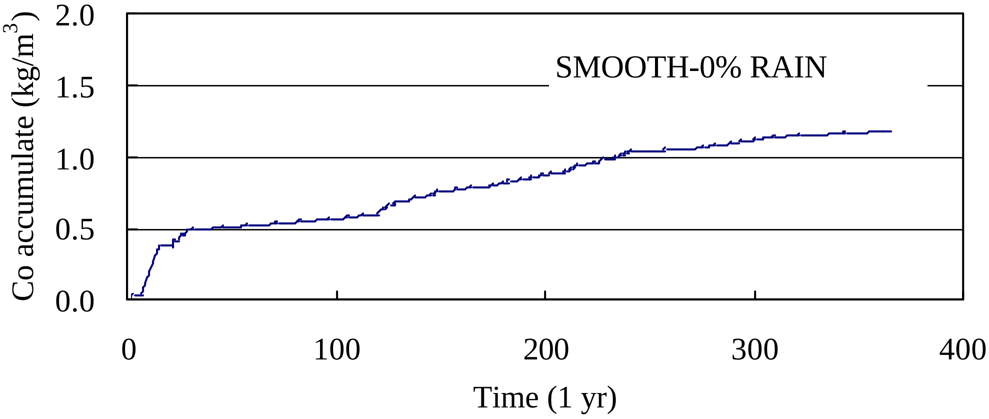
**Zone 1: At 100m from coastline in Okinawa**



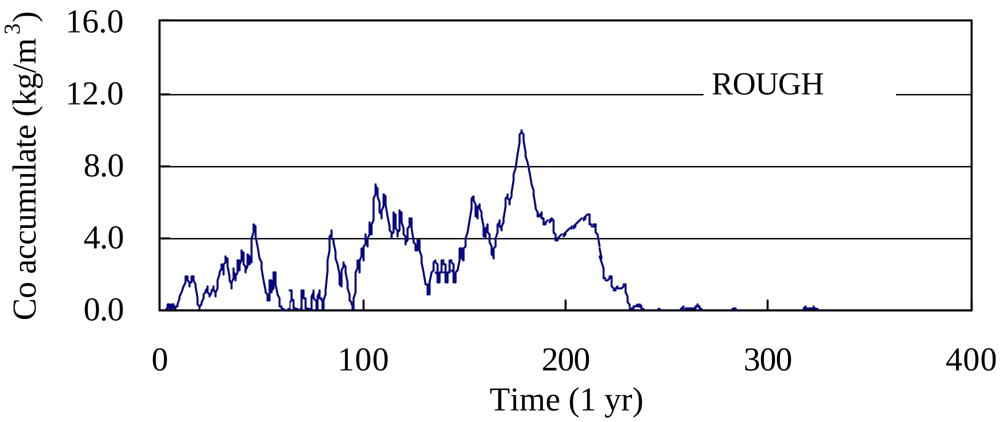



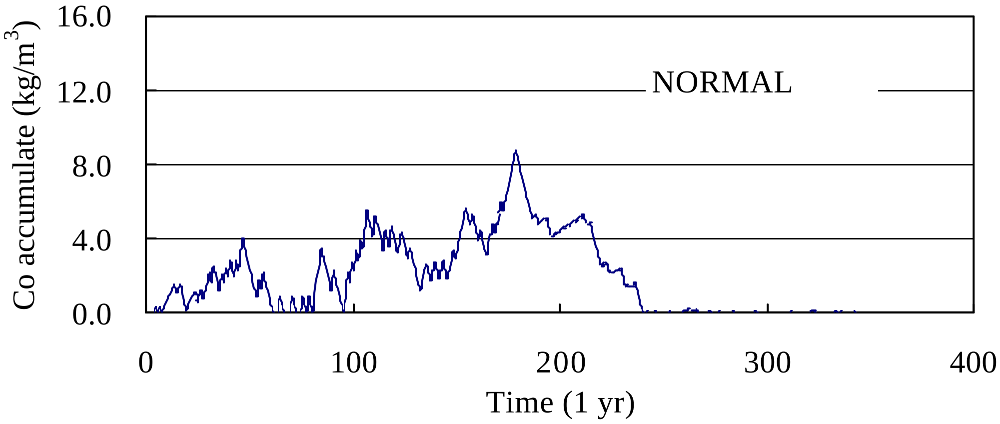



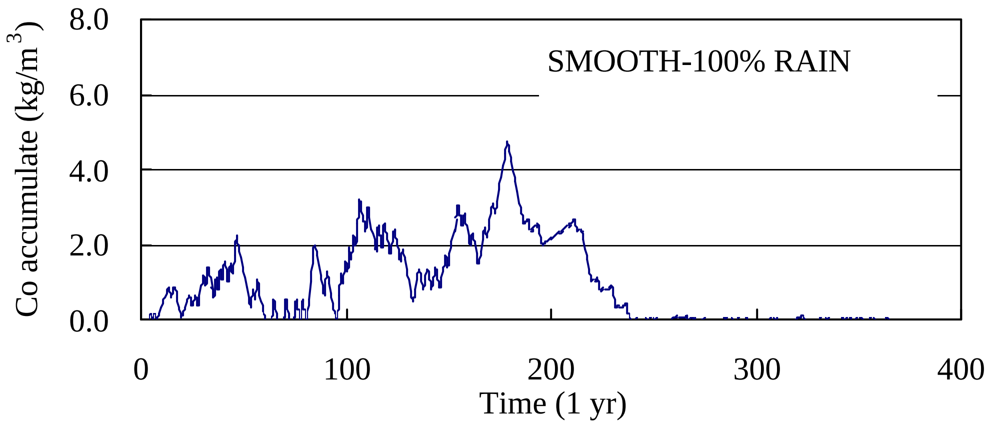

SMOOTH-50% RAIN
Co accumulate (kg/m3)
8.0
6.0
4.0
2.0
0.0
0
50
100
150
200
250
300
350
400
Time (1 yr)

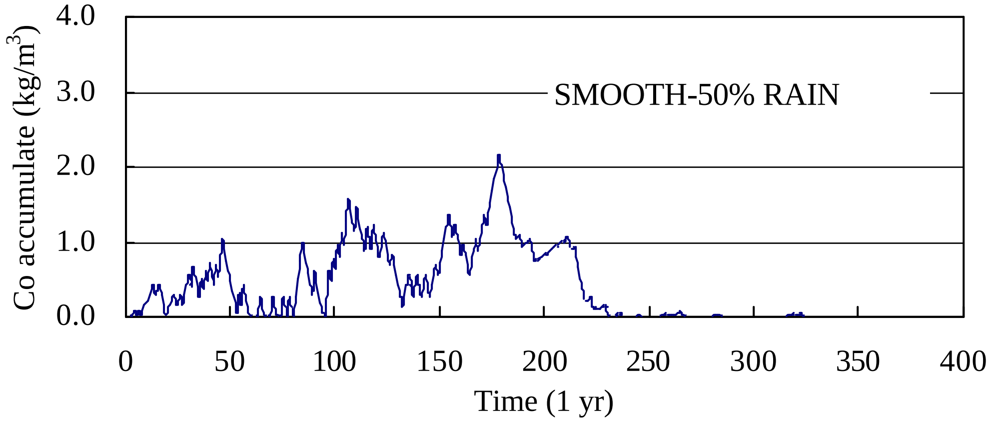

SMOOTH-0% RAIN
Co accumulate (kg/m3)
2.0
1.5
1.0
0.5
0.0
0
100
200
300
400
Time (1 yr)

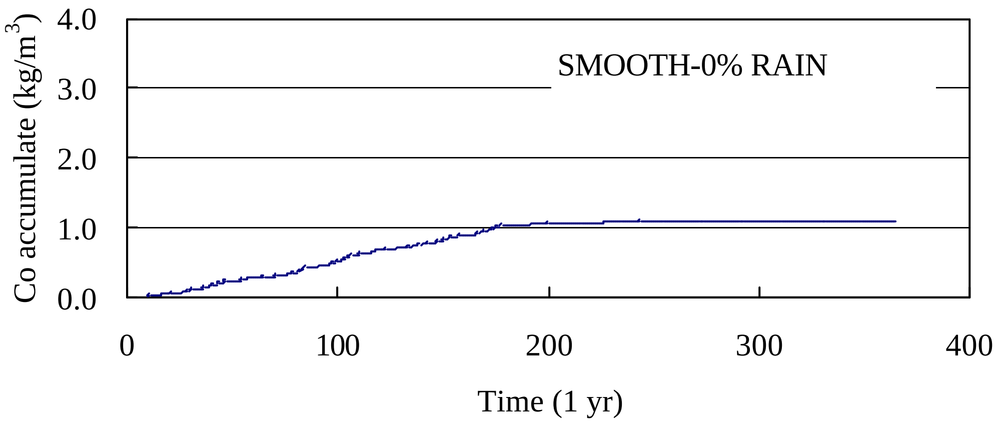
**Zone 2: At 100m from coastline in Japan Sea Coastline**



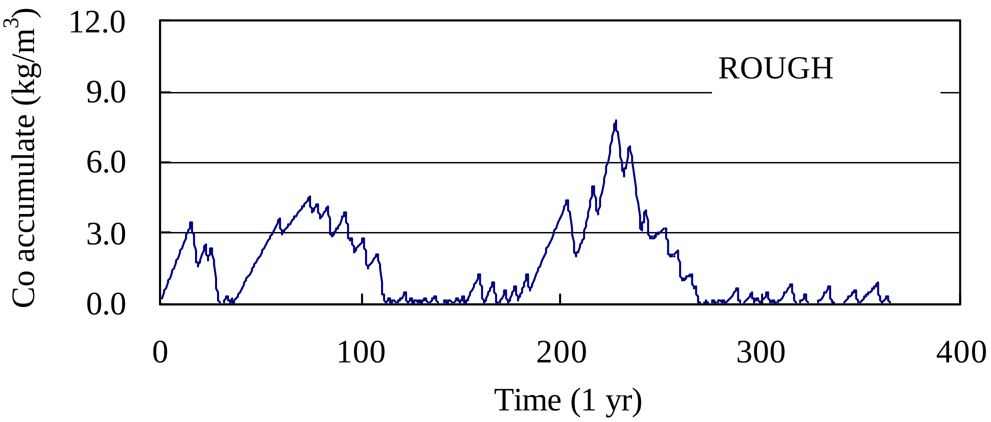



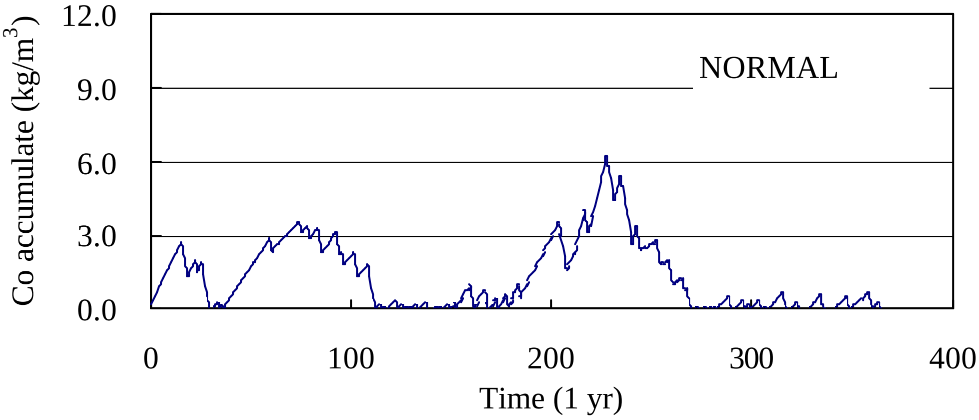



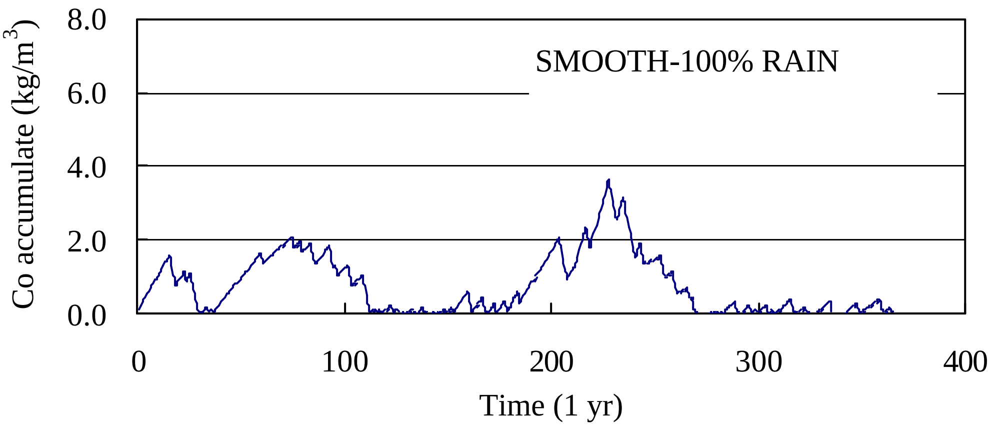

SMOOTH-50% RAIN
Co accumulate (kg/m3)
4.0
3.0
2.0
1.0
0.0
0
50
100
150
200
250
300
350
400
Time (1 yr)

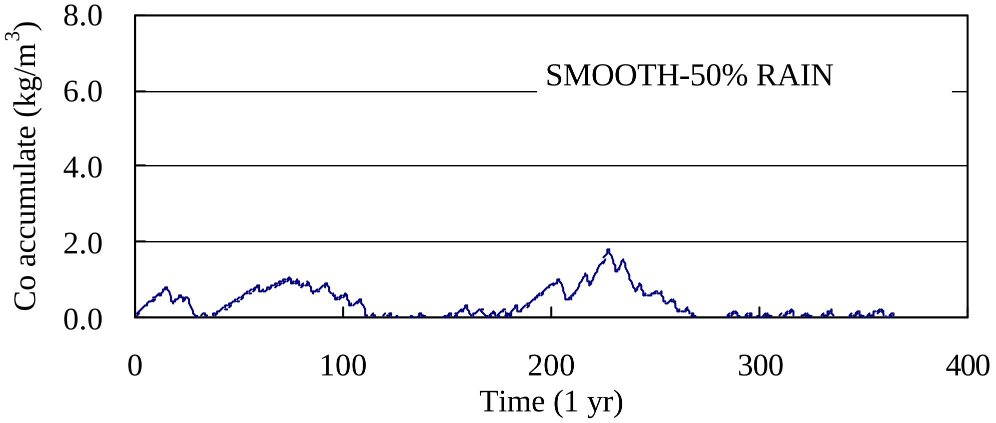

SMOOTH-0% RAIN
Co accumulate (kg/m3)
4.0
3.0
2.0
1.0
0.0
0
100
200
300
400
Time (1 yr)

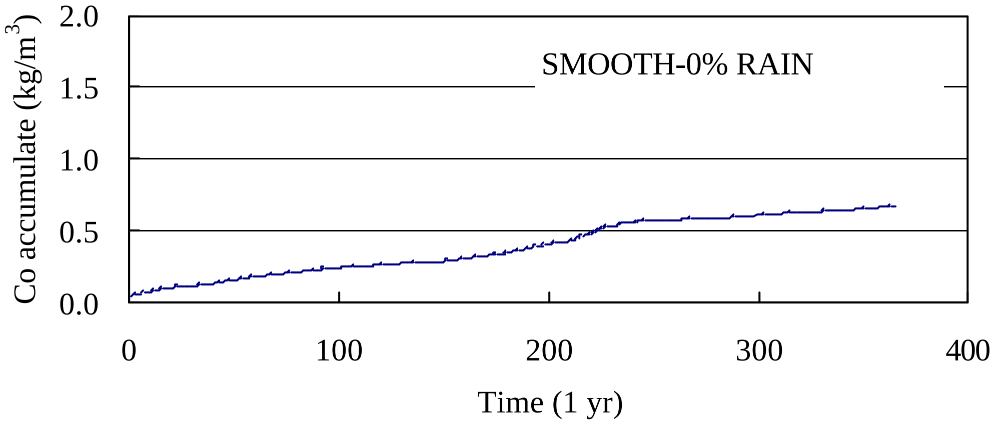
**Zone 3: At 100m from coastline in Pacific Ocean Coastline**



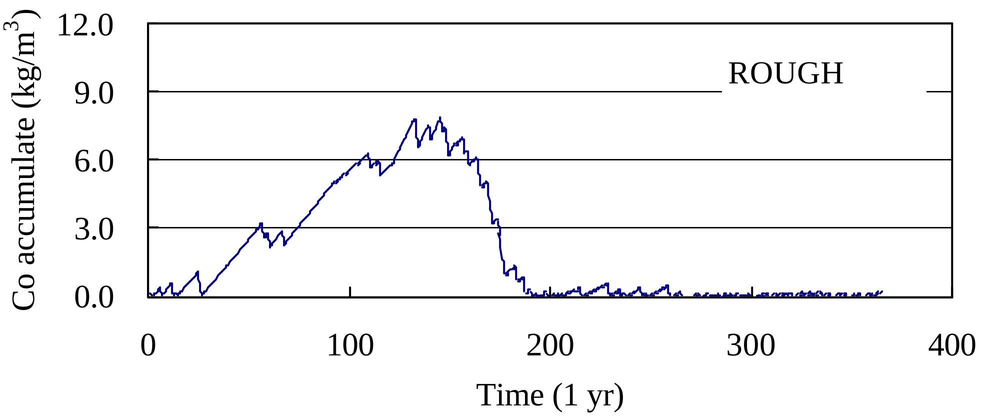



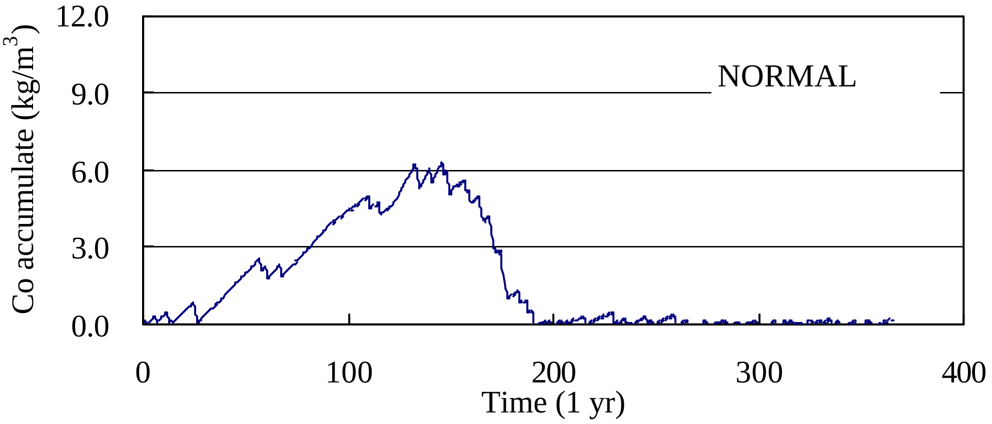



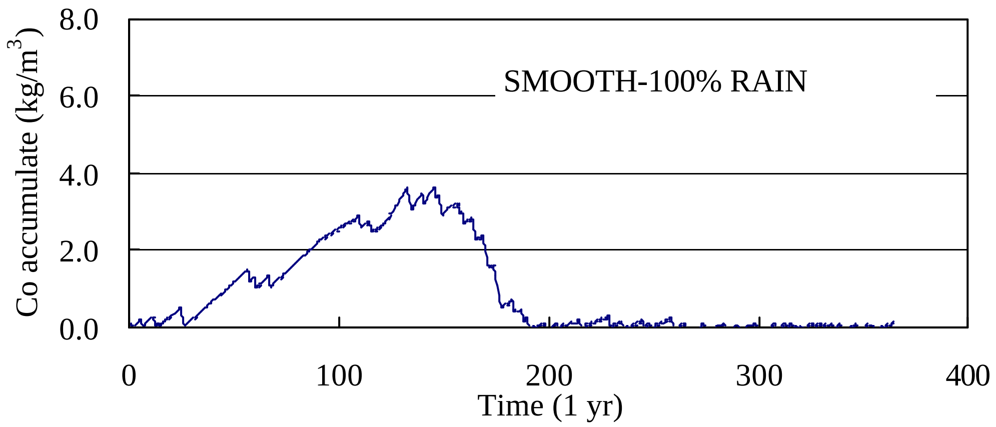

SMOOTH-50% RAIN
Co accumulate (kg/m3)
8.0
6.0
4.0
2.0
0.0
0
100
200
300
400
Time (1 yr)

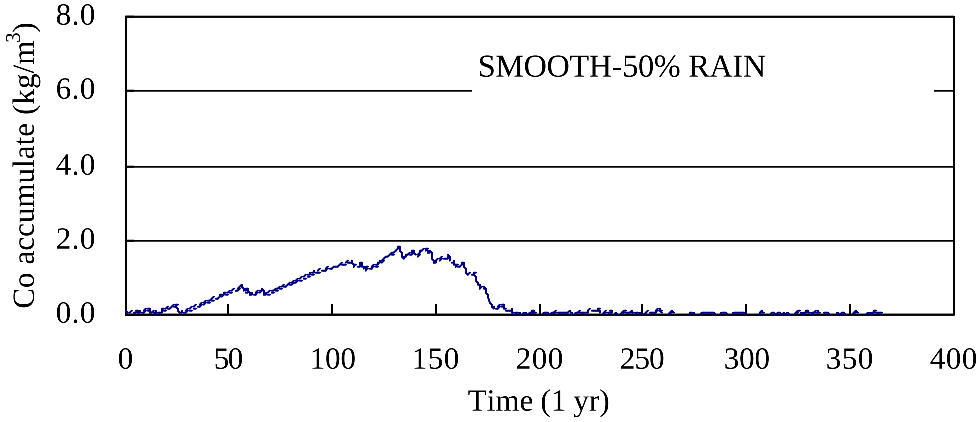

SMOOTH-0% RAIN
Co accumulate (kg/m3)
2.0
1.5
1.0
0.5
0.0
0
100
200
300
400
Time (1 yr)

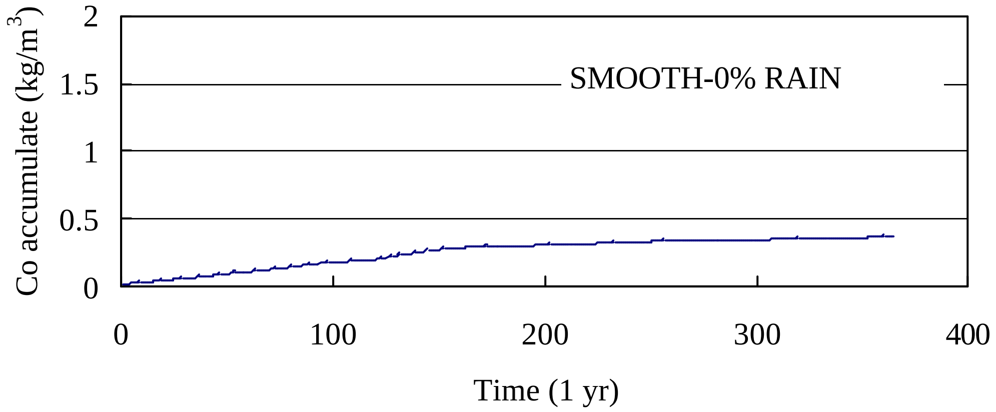
## Zone 4: At 100m from coastline in Chuubu to Nagasaki



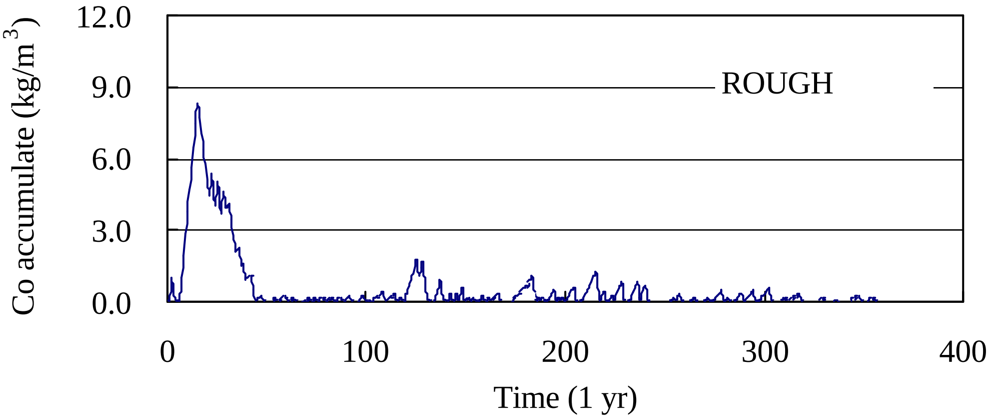



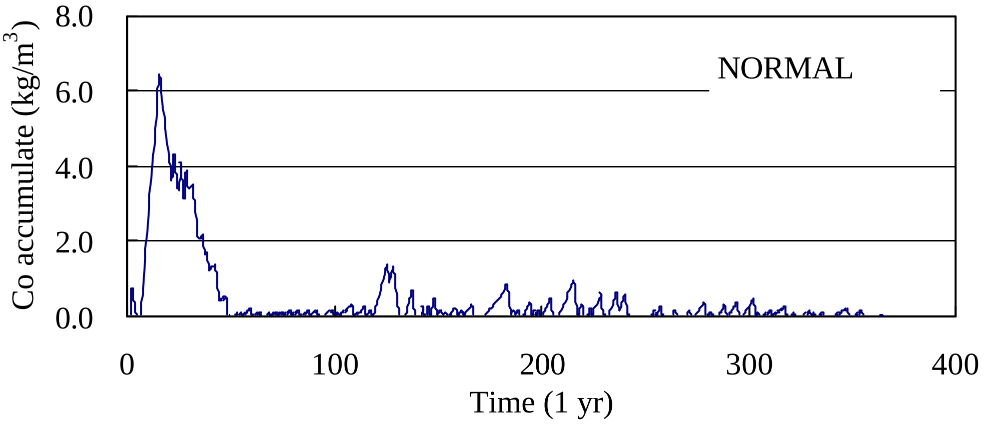



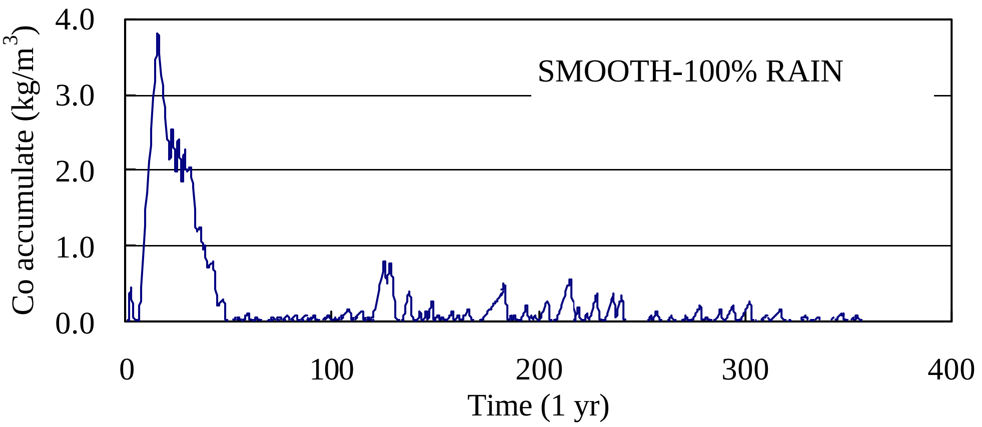

SMOOTH-50% RAIN
Co accumulate (kg/m3)
8.0
6.0
4.0
2.0
0.0
0
50
100
150
200
250
300
350
400
Time (1 yr)

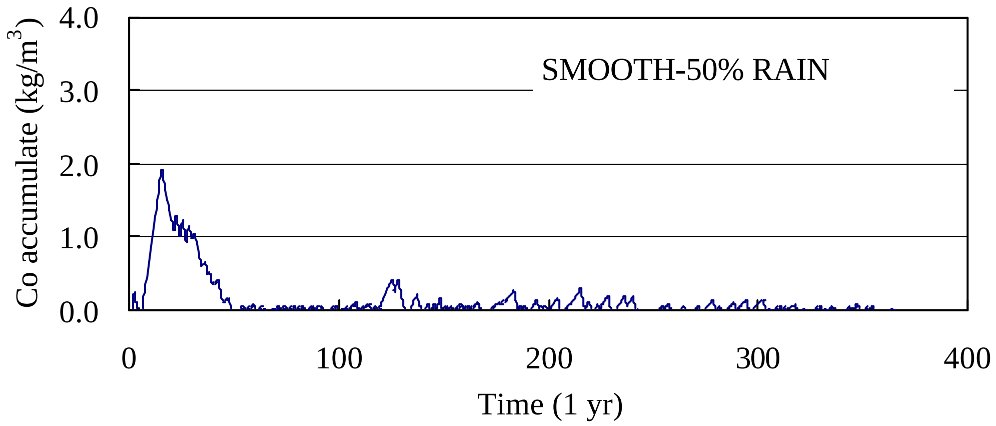

SMOOTH-0% RAIN
Co accumulate (kg/m3)
2
1.5
1
0.5
0
0
100
200
300
400
Time (1 yr)

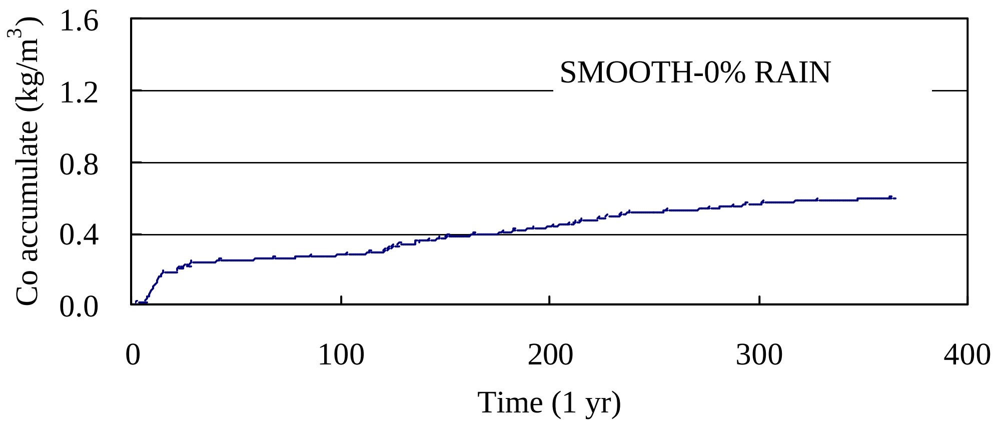
**Zone 1: At 300m from coastline in Okinawa**



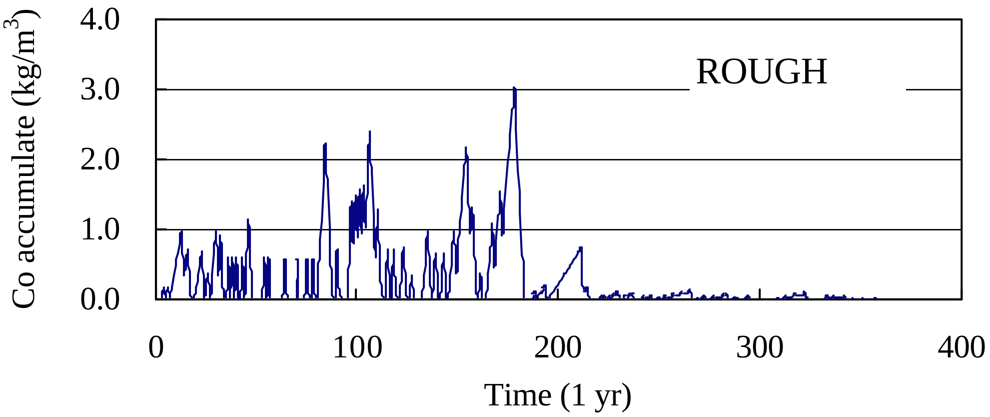



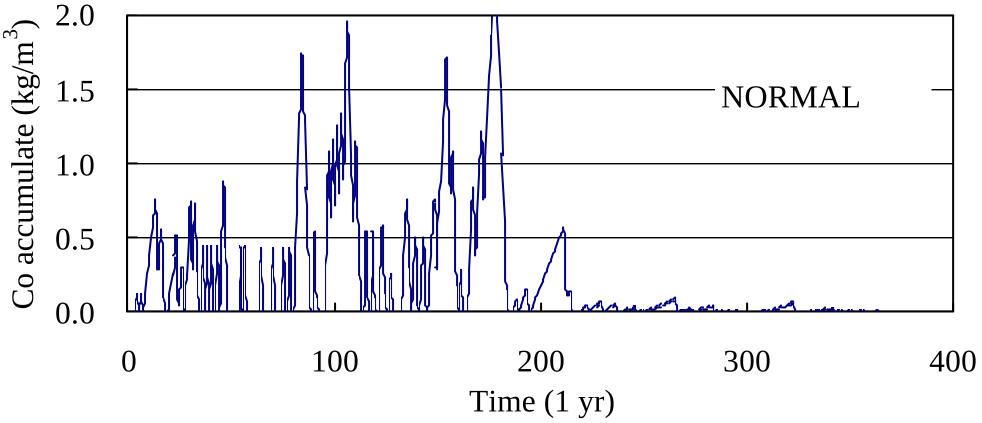



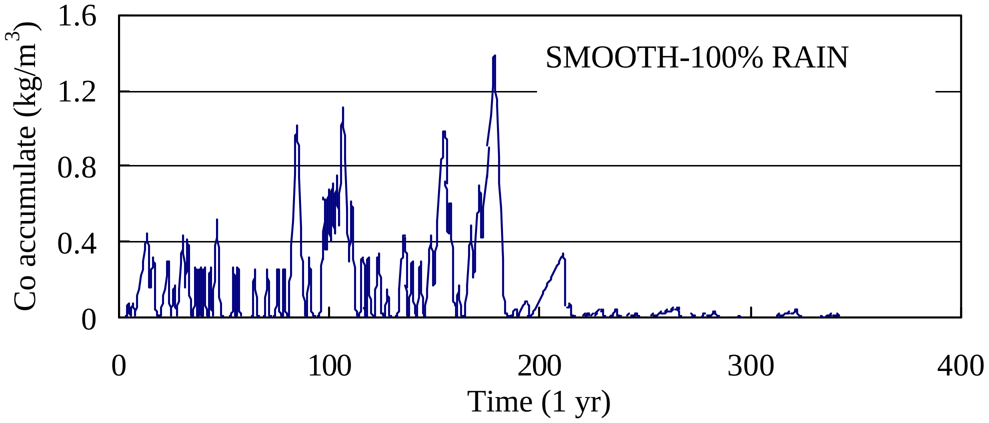

Co accumulate (kg/m3)
4.0
3.0
2.0
1.0
0.0
SMOOTH-50% RAIN
0
100
200
300
400
Time (1 yr)

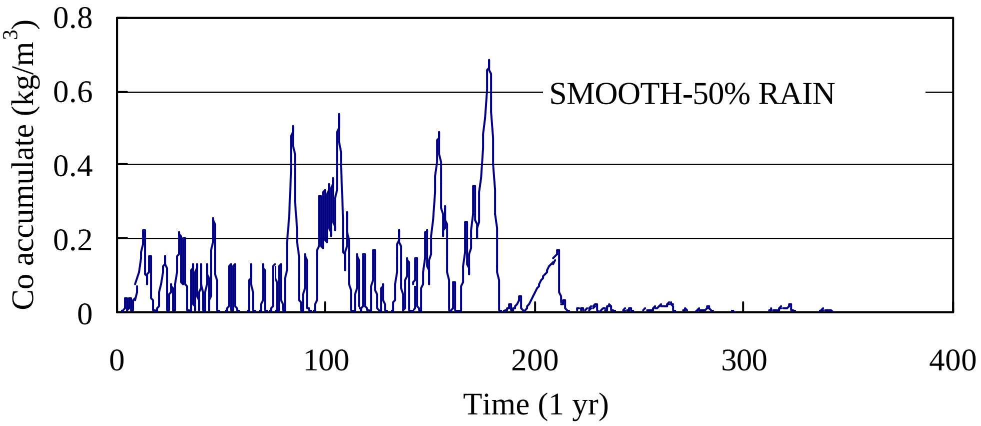

Co accumulate (kg/m3)
1.6
1.2
0.8
0.4
0.0
SMOOTH-0% RAIN
0
100
200
300
400
Time (1 yr)

## Zone 2: At 300m from coastline in Japan Sea Coastline

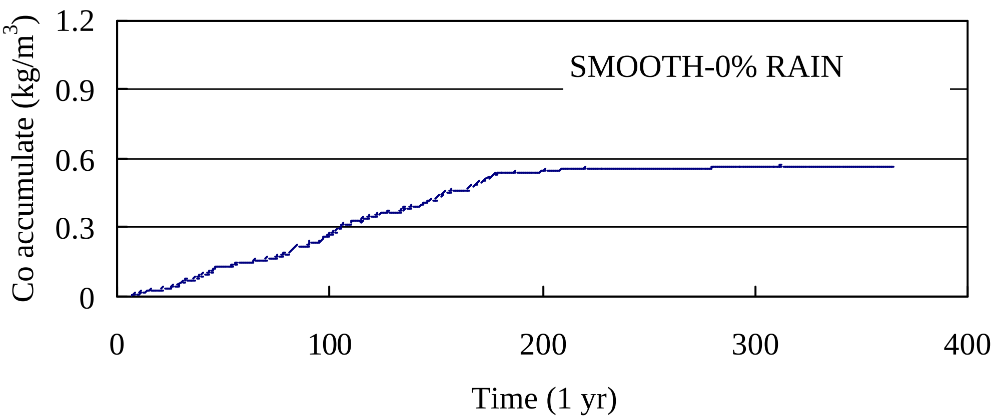


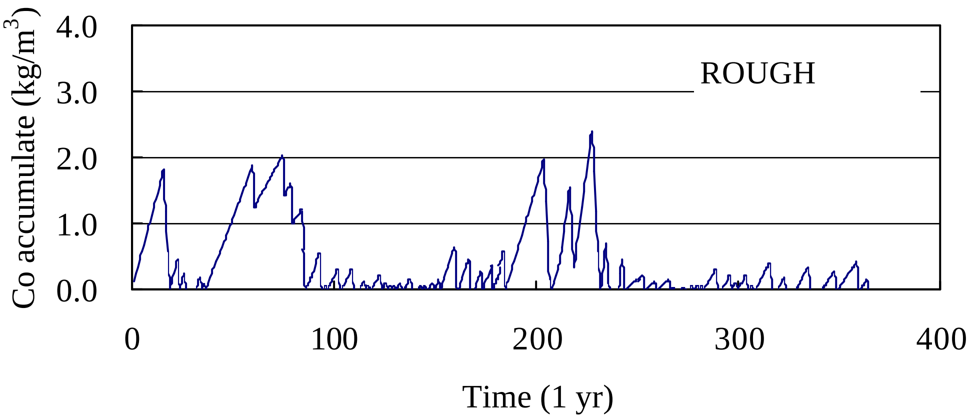


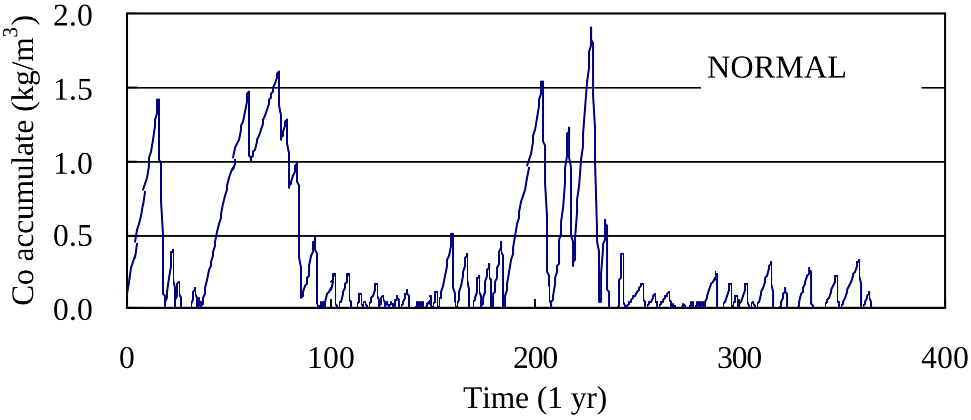
SMOOTH-50% RAIN
Co accumulate (kg/m3)
0.8
0.6
0.4
0.2
0
0
100
200
300
400
Time (1 yr)

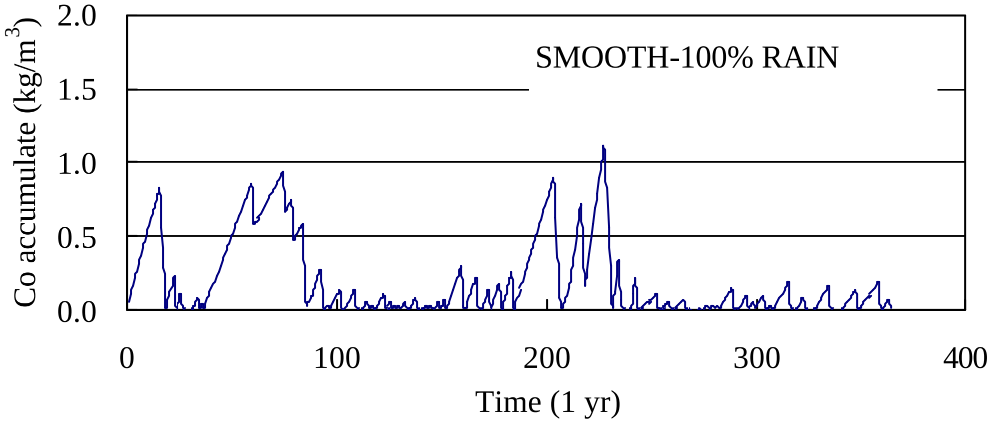



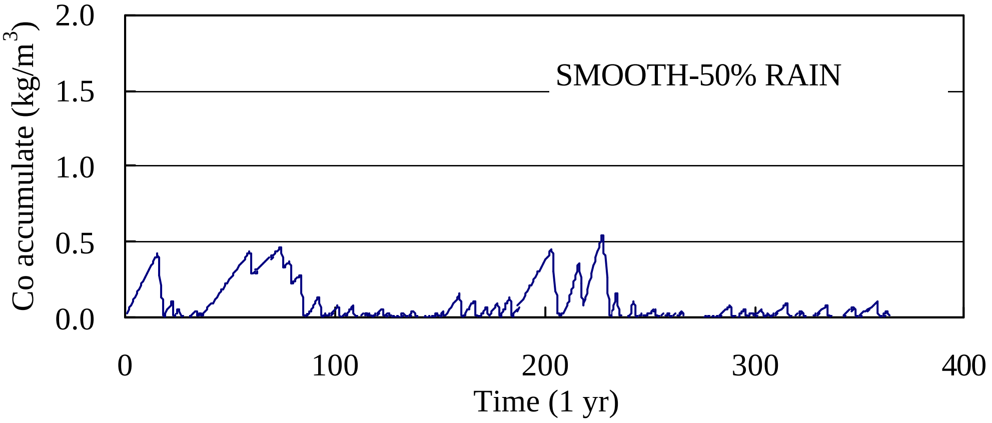
SMOOTH-0% RAIN
Co accumulate (kg/m3)
1.2
0.9
0.6
0.3
0
0
100
200
300
400
Time (1 yr)

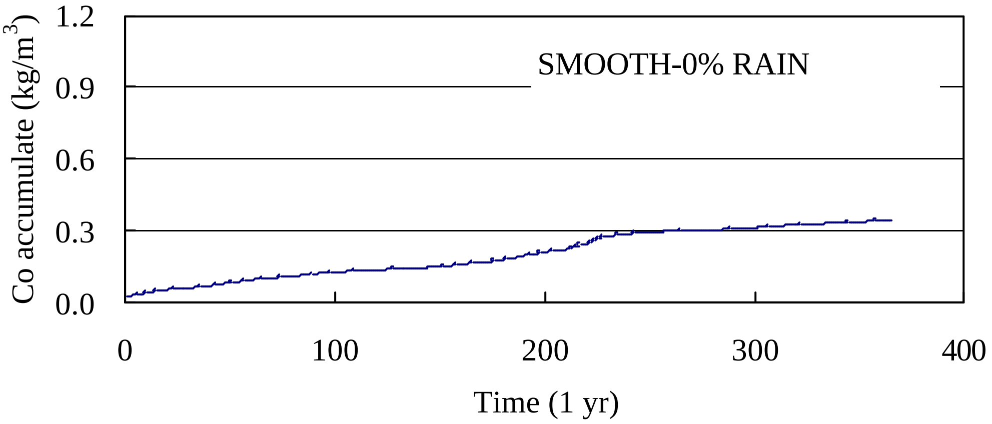
**Zone 3: At 300m from coastline in Pacific Ocean Coastline**



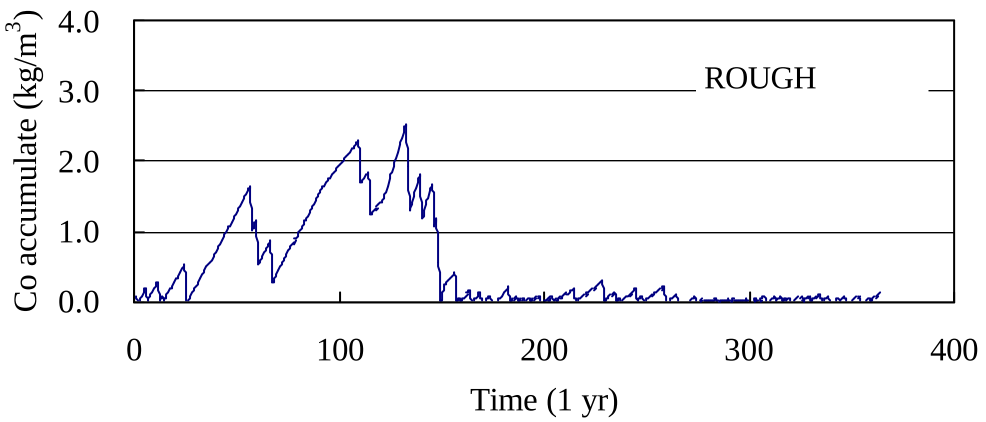



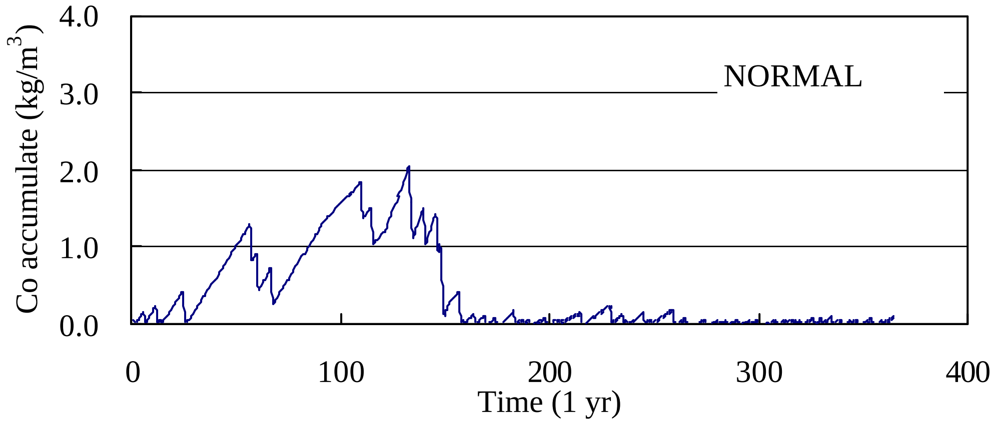



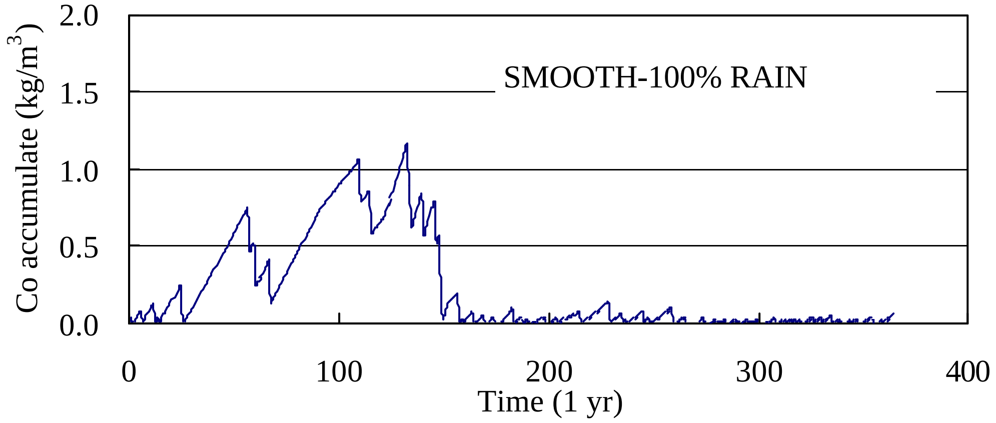

SMOOTH-50% RAIN
Co accumulate (kg/m3)
2.0
1.5
1.0
0.5
0.0
0
100
200
300
400
Time (1 yr)

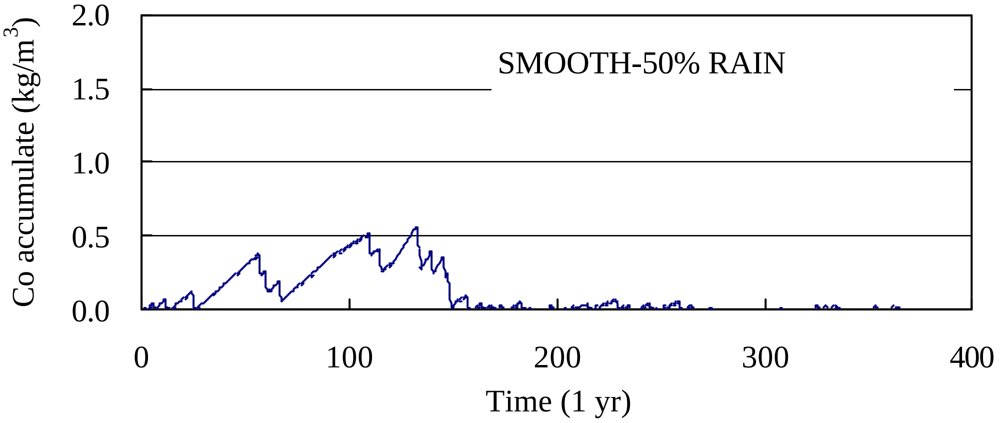

SMOOTH-0% RAIN
Co accumulate (kg/m3)
1.2
0.9
0.6
0.3
0.0
0
100
200
300
400
Time (1 yr)

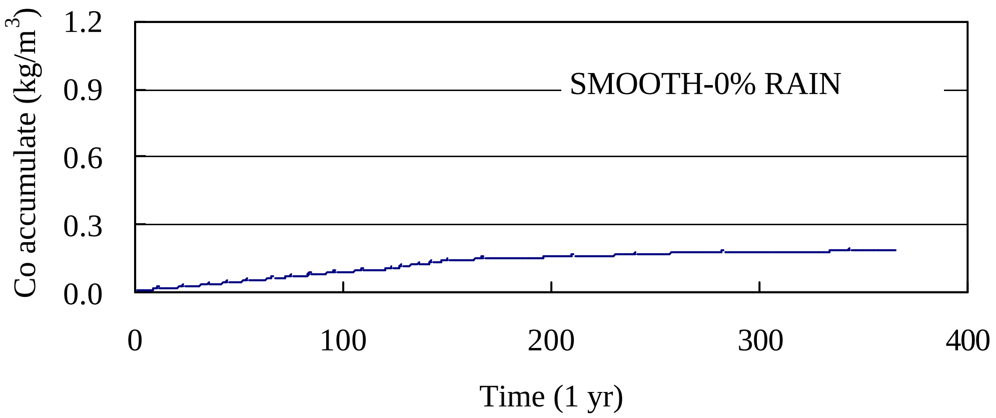
**Zone 4: At 300m from coastline in Chuubu to Nagasaki**



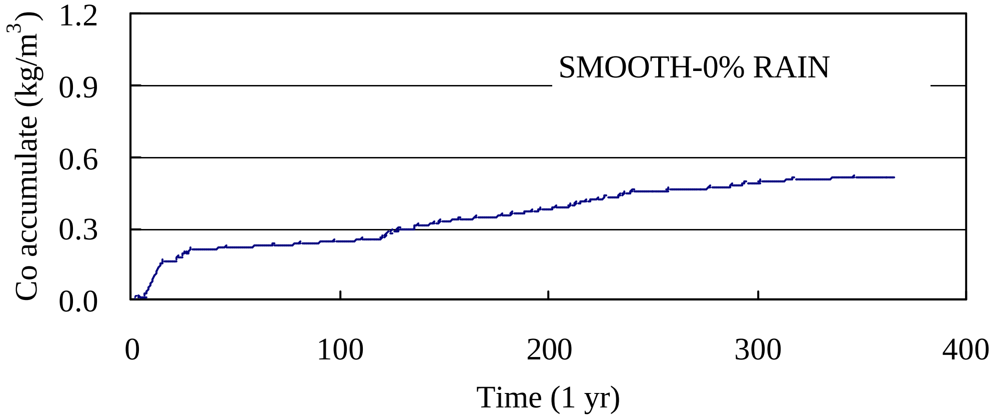




SMOOTH-50% RAIN
Co accumulate (kg/m3)
2.0
1.5
1.0
0.5
0.0
0
100
200
300
400
Time (1 yr)

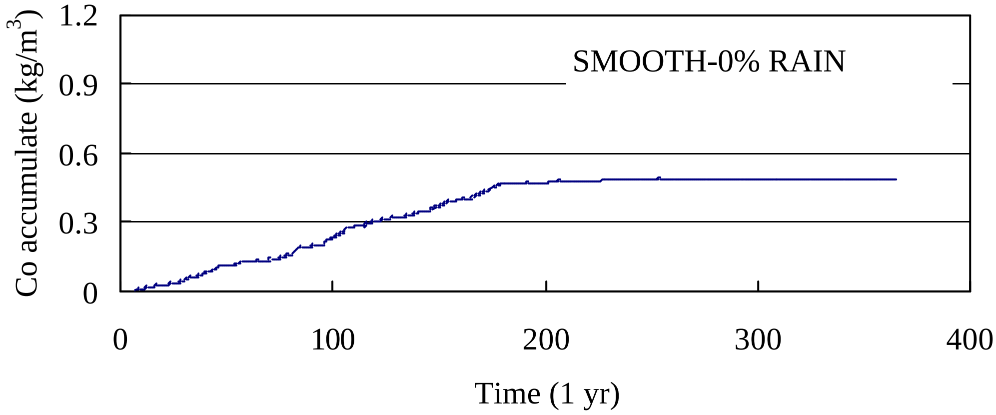

SMOOTH-0% RAIN
Co accumulate (kg/m3)
1.2
0.9
0.6
0.3
0.0
0
100
200
300
400
Time (1 yr)

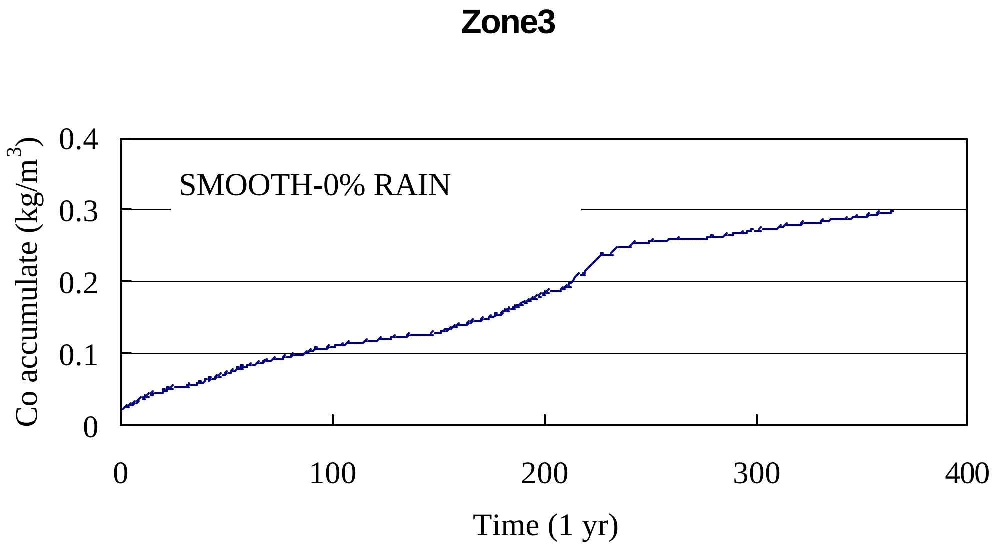
**Zone1-Zone4: 500m distance from seashore for indoor structures only [Others are very low surface chloride concentration at this distance]**

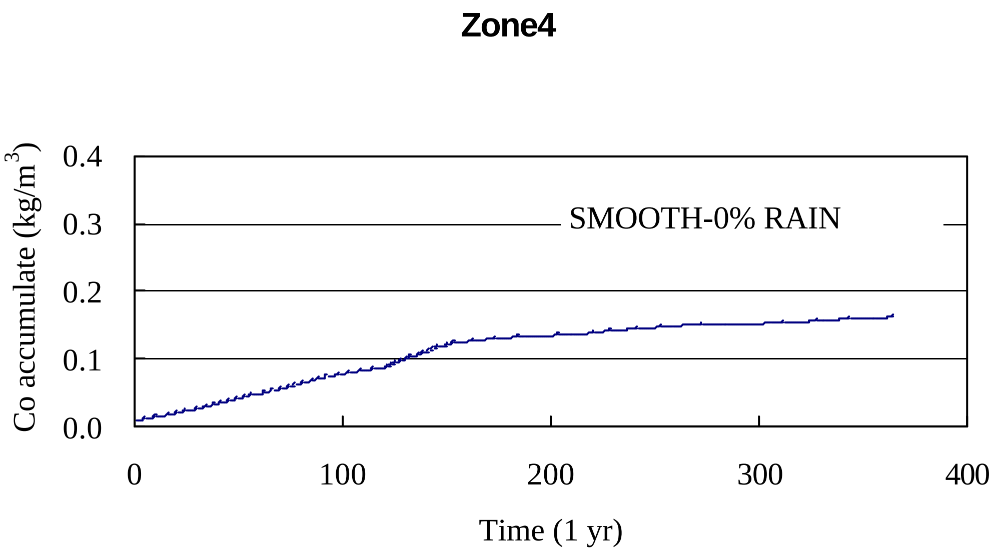
**Zone1**




**Zone2**



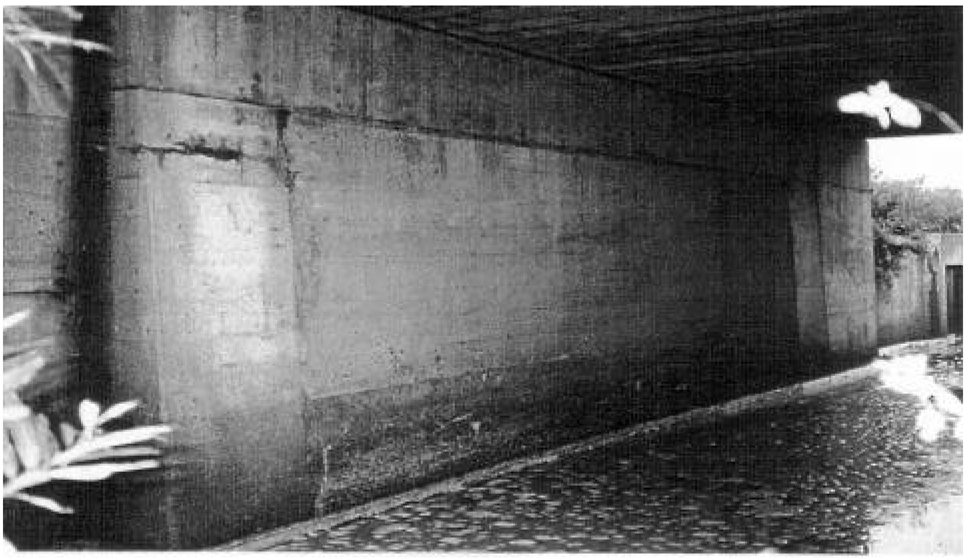

Zone3
SMOOTH-0% RAIN
Co accumulate (kg/m3)
0.4
0.3
0.2
0.1
0
0
100
200
300
400
Time (1 yr)


Zone4
SMOOTH-0% RAIN
Co accumulate (kg/m3)
0.4
0.3
0.2
0.1
0.0
0
100
200
300
400
Time (1 yr)

# Appendix B

# The investigated data by Public Works Research Institute for model verification

| STRUCTURE NO. | A1017 | | |
|---|---|---|---|
| **Structural input data** | **Value** | **Experimental CL⁻ data** | |
| | | **Depth (cm)** | **Value (kg/m$^3$)** |
| Time after construction, T (yrs) | 31 | | |
| Structural area (select one) | Hokkaido | 1 | 1.13 |
| Distance from seashore (m) | 200 | 3 | 0.93 |
| Height from the mean sea level (m | 8 | 5 | 0.84 |
| Structure Type (select one) | Abutment | 7 | 0.35 |
| Apparent Strength, f'c (MPa) | 19 | 9 | 0.14 |
| **Material input data** | **Value** | | |
| Cement type (select one) | OPC | | |
| Estimated w/c = | 0.66 | | |
| Weight of cement per m$^3$ (kg) | 256 | | |

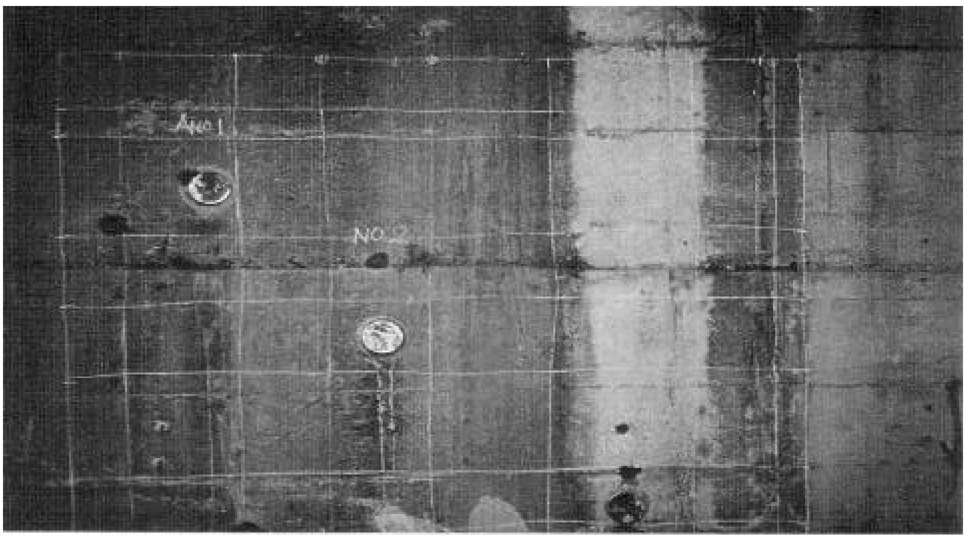


| STRUCTURE NO. | B1013 |
|---|---|
| **Structural input data** | **Value** |
| Time after construction, T (yrs) | 30 |
| Structural area (select one) | Iwate |
| Distance from seashore (m) | 100 |
| Height from the mean sea level (m | 7 |
| Structure Type (select one) | foundation |
| Apparent Strength, f'c (MPa) | 30 |

| **Material input data** | **Value** |
|---|---|
| Cement type (select one) | OPC |
| Estimated w/c = | 0.56 |
| Weight of cement per $m^3$ (kg) | 300 |

**Experimental $CL^-$ data**

| **Depth (cm)** | **Value (kg/$m^3$)** |
|---|---|
| 1 | 1.89 |
| 3 | 4.09 |
| 5 | 2.50 |
| 7 | 1.33 |
| 9 | 0.23 |



| STRUCTURE NO. | B2009 | | |
|---|---|---|---|
| **Structural input data** | **Value** | **Experimental $CL^-$ data** | |
| | | **Depth (cm)** | **Value (kg/m$^3$)** |
| Time after construction, T (yrs) | 29 | 1 | 4.91 |
| Structural area (select one) | yamagata | 3 | 3.50 |
| Distance from seashore (m) | 10 | 5 | 3.07 |
| Height from the mean sea level (m | 5 | 7 | 2.24 |
| Structure Type (select one) | Retaining wall | 9 | 1.18 |
| Apparent Strength, f'c (MPa) | 12.2 | | |
| **Material input data** | **Value** | | |
| Cement type (select one) | OPC | | |
| Estimated w/c = | 0.76 | | |
| Weight of cement per m$^3$ (kg) | 234 | | |

| STRUCTURE NO. | D2016 |
|---|---|

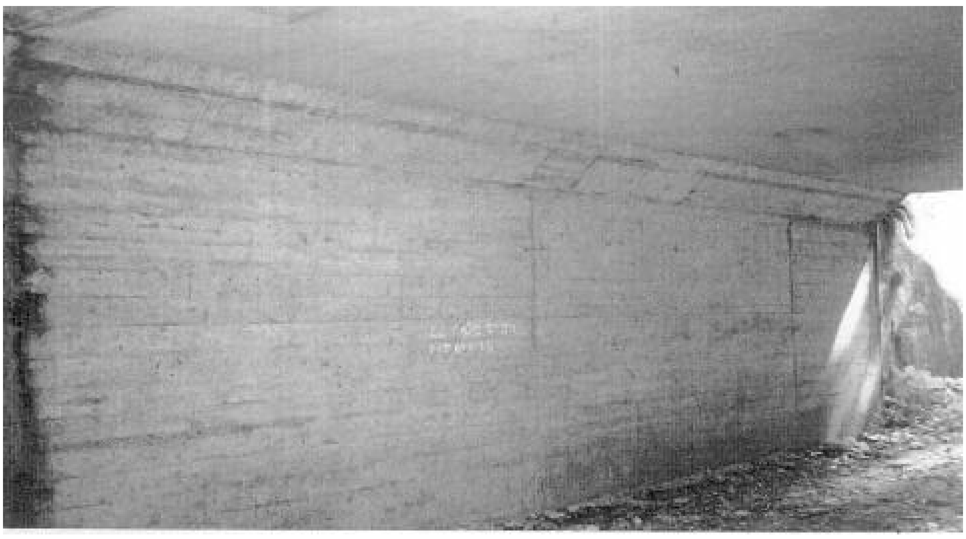
| **Structural input data** | **Value** |
|---|---|
| Time after construction, T (yrs) | 35 |
| Structural area (select one) | Ichikawa |
| Distance from seashore (m) | 30 |
| Height from the mean sea level (m | 4 |
| Structure Type (select one) | Retaining wall |
| Apparent Strength, f'c (MPa) | 23.2 |

| **Material input data** | **Value** |
|---|---|
| Cement type (select one) | OPC |
| Estimated w/c = | 0.62 |
| Weight of cement per $m^3$ (kg) | 266 |

**Experimental $CL^-$ data**

| **Depth (cm)** | **Value ($kg/m^3$)** |
|---|---|
| 1 | 0.60 |
| 3 | 0.58 |
| 5 | 0.31 |
| 7 | 0.14 |
| 9 | 0.07 |

| STRUCTURE NO. | D3008 | | |
|---|---|---|---|
| **Structural input data** | **Value** | **Experimental CL⁻ data** | |
| | | **Depth (cm)** | **Value (kg/m³)** |
| Time after construction, T (yrs) | 36 | 1 | 0.10 |
| Structural area (select one) | Toyama | 3 | 0.03 |
| Distance from seashore (m) | 300 | 5 | 0.03 |
| Height from the mean sea level (m | 12.5 | 7 | 0.05 |
| Structure Type (select one) | Box culvert | 9 | 0.03 |
| Apparent Strength, f'c (MPa) | 37.4 | | |
| **Material input data** | **Value** | | |
| Cement type (select one) | OPC | | |
| Estimated w/c = | 0.50 | | |
| Weight of cement per $m^3$ (kg) | 312 | | |



| STRUCTURE NO. | G1026 |
|---|---|

| Structural input data | Value |
|---|---|
| Time after construction, T (yrs) | 29 |
| Structural area (select one) | Shimane |
| Distance from seashore (m) | 50 |
| Height from the mean sea level (m | 5 |
| Structure Type (select one) | T-shape abutment |
| Apparent Strength, f'c (MPa) | 11.4 |
| **Material input data** | **Value** |
| Cement type (select one) | OPC |
| Estimated w/c = | 0.77 |
| Weight of cement per $m^3$ (kg) | 234 |

**Experimental $CL^-$ data**

| Depth (cm) | Value ($kg/m^3$) |
|---|---|
| 1 | 0.20 |
| 3 | 0.35 |
| 5 | 4.34 |
| 7 | 3.99 |
| 9 | 3.11 |

| STRUCTURE NO. | G3003 |
|---|---|
| **Structural input data** | **Value** |
| Time after construction, T (yrs) | 18 |
| Structural area (select one) | Tottori |
| Distance from seashore (m) | 50 |
| Height from the mean sea level (m | 4 |
| Structure Type (select one) | Box culvert |
| Apparent Strength, f'c (MPa) | 19 |
| **Material input data** | **Value** |
| Cement type (select one) | OPC |
| Estimated w/c = | 0.66 |
| Weight of cement per $m^3$ (kg) | 260 |

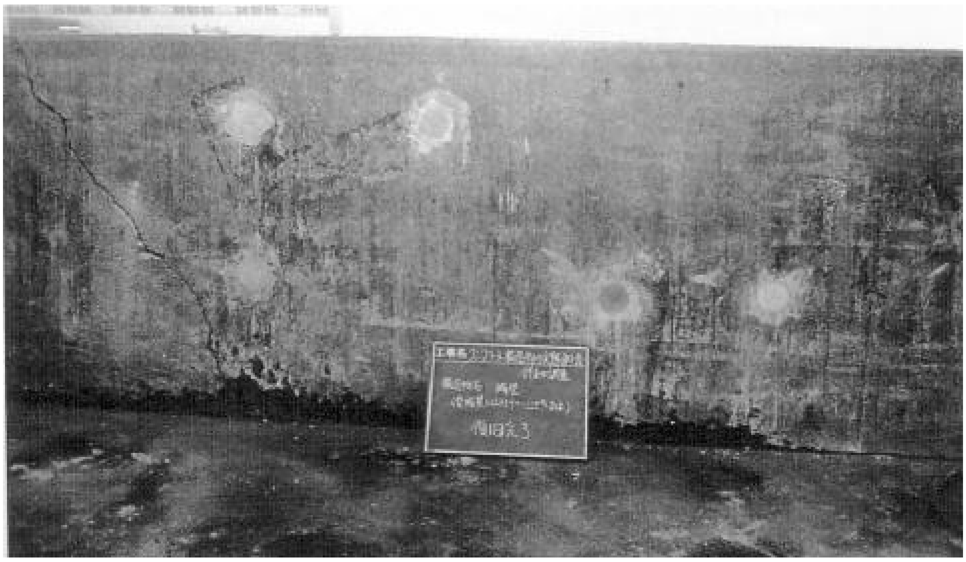
**Experimental $CL^-$ data**

| Depth (cm) | Value ($kg/m^3$) |
|---|---|
| 1 | 8.26 |
| 3 | 13.94 |
| 5 | 9.30 |
| 7 | 5.11 |
| 9 | 2.33 |


| STRUCTURE NO. | H2018 |
|---|---|
| **Structural input data** | **Value** |
| Time after construction, T (yrs) | 36 |
| Structural area (select one) | Ehime |
| Distance from seashore (m) | 50 |
| Height from the mean sea level (m | 5 |
| Structure Type (select one) | Gravity Structure |
| Apparent Strength, f'c (MPa) | 32.8 |
| **Material input data** | **Value** |
| Cement type (select one) | OPC |
| Estimated w/c = | 0.53 |
| Weight of cement per m$^3$ (kg) | 295 |

**Experimental CL$^-$ data**

| Depth (cm) | Value (kg/m$^3$) |
|---|---|
| 1 | 2.85 |
| 3 | 2.79 |
| 5 | 2.62 |
| 7 | 2.54 |
| 9 | 2.85 |

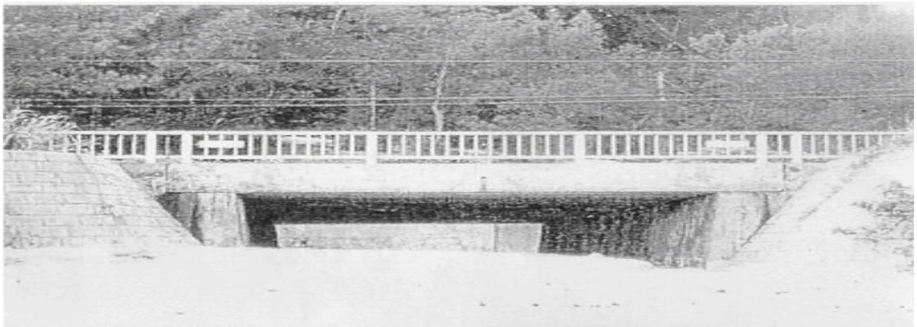


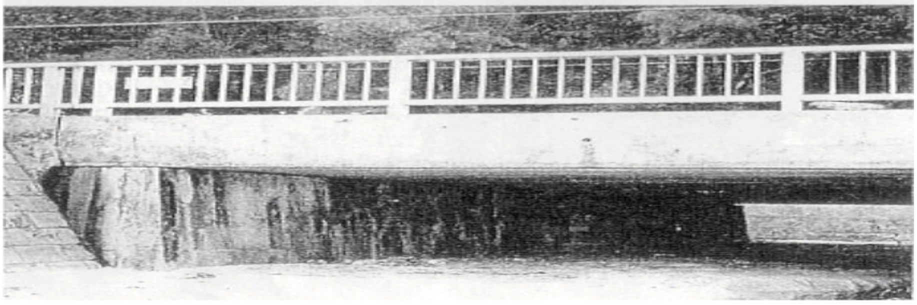
| STRUCTURE NO. | H4017 |
|---|---|
| **Structural input data** | **Value** |
| Time after construction, T (yrs) | 23 |
| Structural area (select one) | Ehime |
| Distance from seashore (m) | 251 |
| Height from the mean sea level (m | 0 |
| Structure Type (select one) | Gutter |
| Apparent Strength, f'c (MPa) | 31 |
| **Material input data** | **Value** |
| Cement type (select one) | OPC |
| Estimated w/c = | 0.55 |
| Weight of cement per $m^3$ (kg) | 295 |

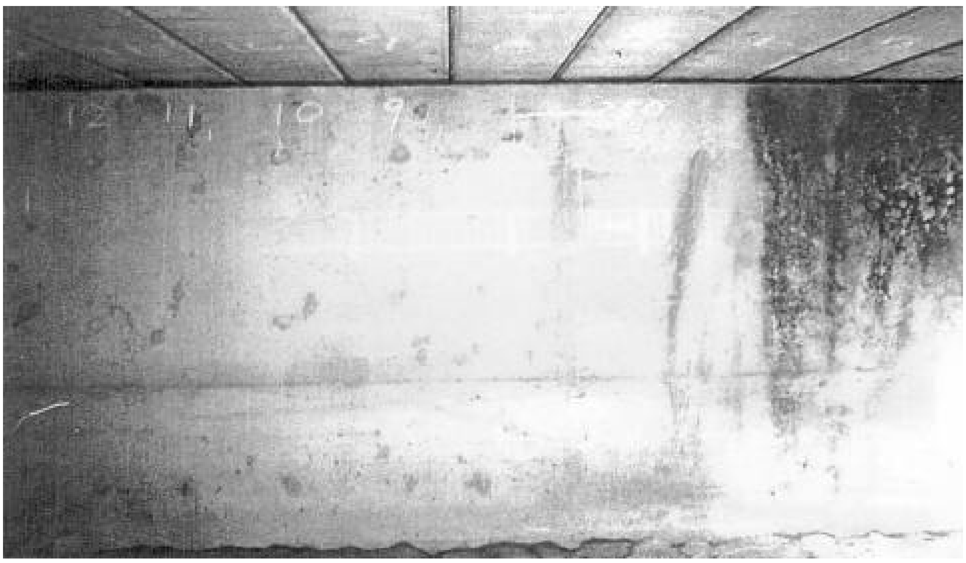
**Experimental $CL^-$ data**

| **Depth (cm)** | **Value ($kg/m^3$)** |
|---|---|
| 1 | 2.20 |
| 3 | 2.68 |
| 5 | 2.06 |
| 7 | 1.71 |
| 9 | 1.66 |

| STRUCTURE NO. | K1005 | | |
|---|---|---|---|
| **Structural input data** | **Value** | **Experimental $CL^-$ data** | |
| | | **Depth (cm)** | **Value ($kg/m^3$)** |
| Time after construction, T (yrs) | 18 | 1 | 5.42 |
| Structural area (select one) | Okinawa | 3 | 11.79 |
| Distance from seashore (m) | 100 | 5 | 7.92 |
| Height from the mean sea level (m | 0 | 7 | 4.37 |
| Structure Type (select one) | Under bridge members | 9 | 3.08 |
| Apparent Strength, f'c (MPa) | 26 | | |
| **Material input data** | **Value** | | |
| Cement type (select one) | OPC | | |
| Estimated w/c = | 0.59 | | |
| Weight of cement per $m^3$ (kg) | 275 | | |



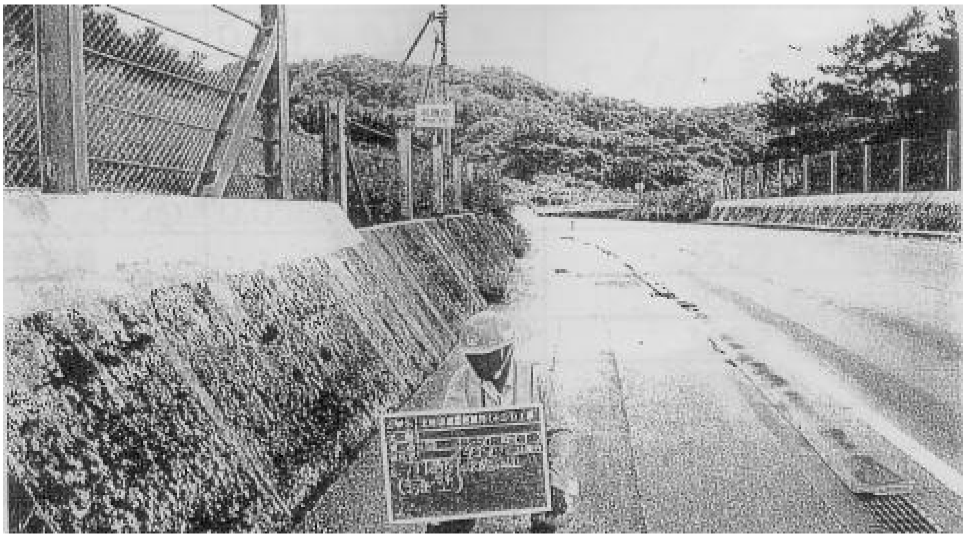




| STRUCTURE NO. | K2005 |
|---|---|
| **Structural input data** | **Value** |
| Time after construction, T (yrs) | 17 |
| Structural area (select one) | Okinawa |
| Distance from seashore (m) | 70 |
| Height from the mean sea level (m | 5 |
| Structure Type (select one) | Gravity structure |
| Apparent Strength, f'c (MPa) | 23.1 |
| **Material input data** | **Value** |
| Cement type (select one) | OPC |
| Estimated w/c = | 0.62 |
| Weight of cement per $m^3$ (kg) | 269 |

**Experimental $CL^-$ data**

| Depth (cm) | Value ($kg/m^3$) |
|---|---|
| 1 | 3.74 |
| 3 | 5.50 |
| 5 | 3.74 |
| 7 | 2.55 |
| 9 | 1.37 |



| STRUCTURE NO. | K3003 | | |
|---|---|---|---|
| **Structural input data** | **Value** | **Experimental $CL^-$ data** | |
| | | **Depth (cm)** | **Value ($kg/m^3$)** |
| Time after construction, T (yrs) | 20 | 1 | 4.26 |
| Structural area (select one) | Okinawa | 3 | 7.26 |
| Distance from seashore (m) | 10 | 5 | 2.32 |
| Height from the mean sea level (m | 0.8 | 7 | 1.17 |
| Structure Type (select one) | Box culvert | 9 | 0.85 |
| Apparent Strength, f'c (MPa) | 28.6 | | |
| **Material input data** | **Value** | | |
| Cement type (select one) | OPC | | |
| Estimated w/c = | 0.57 | | |
| Weight of cement per $m^3$ (kg) | 284 | | |