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LOW CHLORIDE DISTRIBUTION IN CONCRETE STRUCTURES NEAR SEASHORE

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The JSCE design specification for preventing the deterioration of a structure nearby the marine environment has been developing continuously more than 20 years. The specification for a new construction covers all levels of the severity on chloride attack in Japan. Following this design, structures in mild areas have excessive prevention which cause the non-economical asset. At the seashore, the surface chloride concentrations on the outdoor structures were observed that they are extremely different to the specification. Some chlorides on structural surface could be washed out during the raining period. As the result, structures might have a small amount of chloride content despite of it is located nearby the shoreline.

Key Words: *chloride distribution, rain, outdoor structure and marine environment*

1. INTRODUCTION

Life-span prediction of infrastructure is necessary for the guarantee of durable, reliable and safety performances. The sustainable infrastructures are required to maintain their performances for a long life. The time prediction of maintenance, repair and demolition is necessary for computing life-cycled cost of a structure. In Japan, the ranking of the severe locations on chloride attack are in Okinawa, Japan Sea Coastline, and others, respectively[1),2)]. Considering the environmental condition in Okinawa, typhoon and increasing of temperature during July to October are the key factors to explain why the structural deterioration in this zone is significantly high. During Typhoon, huge swells are transformed to break at the shoreline and contributed a large amount of airborne chlorides in to the air. Concrete structures along the Japan Sea Coastline are affected by strong wind during winter. A lot of airborne chlorides are generated during this windy condition, but they could not be compared with the formation during typhoon. In addition, the temperature during winter is low and it leads to retard chloride ions diffusion through concrete structures. Comparing both cases, the most effective parameter on the deterioration of the concrete structures is the amount of airborne chlorides around them. This conclusion had been proved since 1985 by Public Works Research Institute of Japan[3),4),5)] by observing the amounts of airborne chloride throughout Japan as expressed in **Fig.1**.

Logically, structures exposed near seashore might have high chloride distribution. From the literatures, the wetting-drying cycles in tidal zone accelerate the penetration rate of chloride ions[6)]. This effect is called 'the advection movement of water suction from dry to suddenly wet condition'. This statement guides many researchers to think that any structures located in the tidal zone are concerned with rapid chloride ions penetration, steel corrosion and degradation. However, there is a difference between chloride ingression on the structures on land and in the tidal zone. Especially, structures on land are not subjected directly to seawater. In an outdoor structure along the Pacific Ocean Coast, the northern wind direction in winter does not transport airborne chlorides from the ocean to the structural surface; but only the southern wind direction especially in rainy and summer seasons is effective. In general, many researchers had presented that a large amount of airborne chlorides in the atmosphere are distributed since the seashore and then dropped gradually on the ground surface along their transported distances. Thus, the surface chloride contents in the JSCE design specification were related to the distances from seashore[6]. However, the chloride attack in various environments is unable to simulate accurately by a simple proposal as mentioned above. Public Works Research Institute had investigated several types of structural members in a thousands samples all over Japan in 1999[7]. Several investigated data of the outdoor structures contents are dramatically less than the recommended amount by JSCE specification in **Table 1**. However, the samples of investigated data in **Figs.2 to 4** were not the same. The revetment at seashore along the national highway No.160 in Ishikawa Prefecture was investigated the structural age at 35 years with compressive strength at 23N/mm^2 as shown in **Fig.2**. The estimated water to cement ratio is 0.62. Second, the revetment at seashore along the national highway No.11 in Ehime Prefecture was investigated the structural age at 36 years with compressive strength at 33N/mm^2 as shown in **Fig.3**. The estimated water to cement ratio is 0.53. Third, the revetment at seashore along the national highway No.7 in Yamagata Prefecture was investigated the structural age at 28 years with the strength at 12 N/mm^2 as shown in **Fig.4**. The estimated water to cement ratio is 0.75. At the same distance from seashore, the chloride distributions were observed that these were totally different. The chloride distribution in concrete in **Fig.2** was expressed very low value through the concrete depth at less than 0.5 kg/m^3. These results could not be explained by the concepts proposed in the JSCE specification or any literatures. A reason must be discovered in which is able to explain this phenomenon.

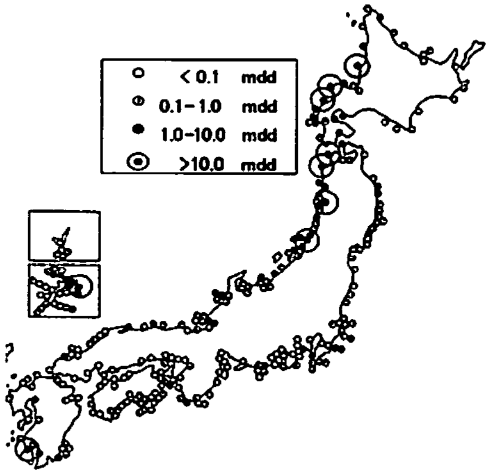

Fig.1 Average airborne chlorides (mg/dm^2/day) around Japan observed by Public Work Research Institute in 1984

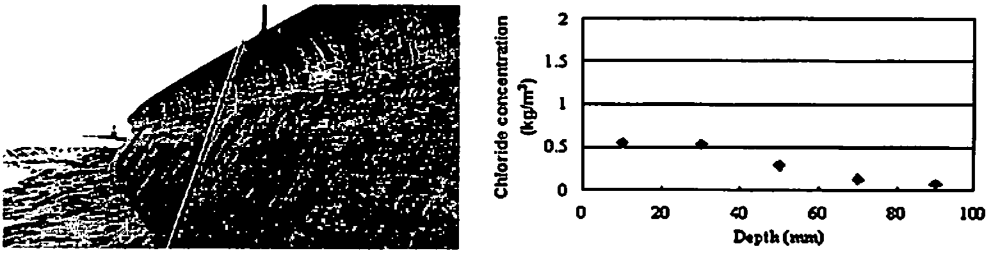

Fig.2 The investigated chloride concentration of a revetment in Ishikawa Prefecture by PWRI[7]

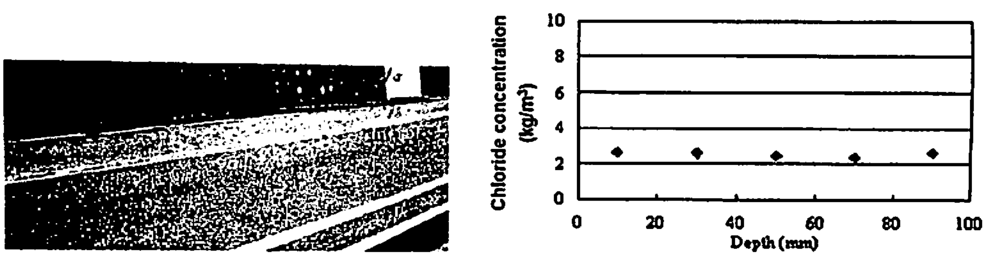

Fig.3 The investigated chloride concentration of a revetment in Ehime Prefecture by PWRI[7]

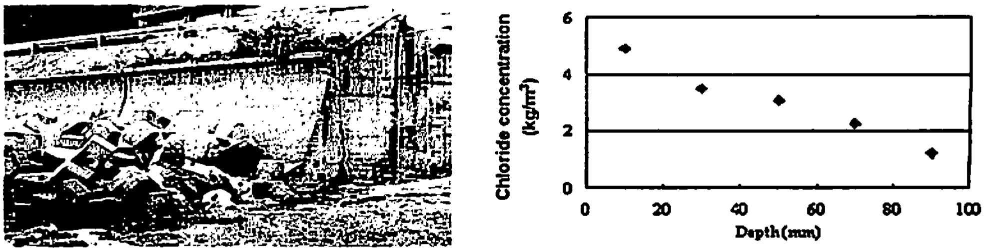

Fig.4 The investigated chloride concentration of a revetment in Yamagata Prefecture by PWRI[7]

Table 1 Recommended chloride contents on concrete surface (kg/m^3) by JSCE Specification in 1999

Splash	Seashore	0.1km	0.25km	0.5km	1km
13.0	9.0	4.5	3.0	2.0	1.5

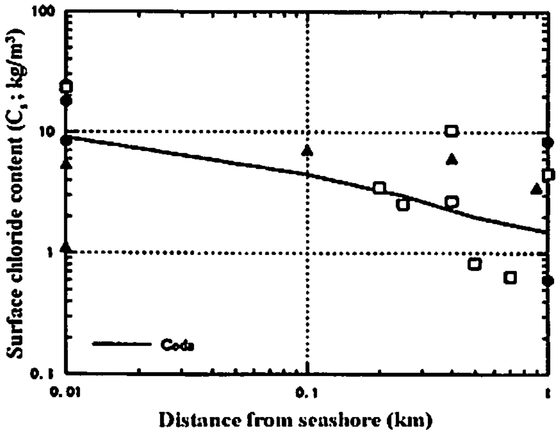

Fig.5 Summarized surface chloride contents from investigated data from PWRI, 1985

The Fick'2nd Law of diffusion is the fundamental concept for chloride migration in heterogeneous materials. It describes the accumulative concentration within the volume as proportion to the local curvature of the concentration gradient. The local rule for accumulation is given by Fick's 2nd law of diffusion;

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

In which, the chloride concentration gradient is under the derivation of time and distance, and D_c is the diffusivity of chloride ions in a particular material. JSCE Design Specification was modified the Fick's 2nd Law to the equation as expressed in the error function;

$$C_{(x,t)} = C_s\left(1 - erf\frac{x}{2\sqrt{D \cdot t}}\right) + C_{(x,0)} \qquad (2)$$

where, $C_{(x,t)}$ is chloride content at the depth of x(cm) and at time of t(year); (kg/m^3), C_s is surface chloride contents (kg/m^3) recommended in **Table 1**, x is distance from concrete surface (cm), D is apparent diffusion coefficient (cm^2/yr)[10], t is serviceability (yrs) and $C_{(x,0)}$ is initial chloride content (kg/m^3)

The investigated data by PWRI, 1985 had been shown the large scatter of surface chloride content between 1-20 kg/m^3 shown in **Fig.5**. This phenomenon is unable to explain only by the diffusion theory. To realize this fact, the environmental factors should be studied. Rain is probably reason to describe this phenomenon.

2. STUDY OF RAIN EFFECT TO CONCRETE STRUCTURES

(1) General

In the past, the surface chloride concentration was recommended in the JSCE Specification on the function of the distance from seashore. The chloride concentration on concrete surface near seashore was shown at 9 kg/m^3. As mentioned above, PWRI investigated data of the chloride concentration in concrete by coring of some structures were not equivalent. In order to understand this fact, surface chloride content is vital to investigate under the effect of rain, which is thought as the main parameter to describe these data.

The amount and duration of precipitation controls the increasing of chloride concentration by dissolving the chloride contents from the structural surface. Structures on land are not subjected directly to seawater. Also, the rainfall flushes the dehydrated salt particles out of the concrete surface.

In addition, volume of rainfall during these periods is also significantly large. The surface chloride contents in outdoor structures are removed by rainfall, remarkably. Thus, the outdoor structures in this zone would not be seriously damaged by chloride attack. Furthermore, rainfall is not only taken into account of outdoor structures, but also indoor structures under the drainage path of the precipitation. The rain drainage path is recognized by changing of concrete color to be a murky color on the surface. The surface erosion due to rainfall is another issue to the progressive increase of surface roughness. The surface roughness is an indicator to classify the capacity in gathering airborne chlorides.

In this study, the impact of rain was observed by the experiment of surface chloride concentration on both indoor and outdoor structures in Kochi Prefecture. The environmental conditions at the investigated structures were simulated in order to explain the cumulative surface chloride content. The average 10-m wind speed at seashore and Amedas environmental data for the analysis is obtained from the database by Japan Meteorological Agency; JMA$^{9)}$. Not only wind and rain are vital, but also the location, roof, concrete surface roughness could not be ignored, as well.

(2) Experimental outlines

The experiments were investigated on the dissolved surface chloride during the rainy season. This aims to realize how much the surface chloride is removed. Furthermore, the surface chloride distribution would be analyzed with the others environmental loads such as wind speed, wind direction and rain. At the concrete structures, the surface was removed in order to test the chloride concentration by the abrasive method$^{14)}$. In this study, the size of 10 x 10 cm, 1-gram sample was removed by using a sand paper. On the same section, the samples were taken in to 5 layers in the same weight. Some tiny particles of a sand paper might be fallen during abrasion, so they should be deducted from the taken samples. Some existing structures in Kochi Prefecture were investigated in their distances from seashore, the structural members which are located both indoor and outdoor. The classification of concrete surface roughness had been divided into smooth, normal, and rough as shown in **Fig.6**, respectively. The surface condition of each investigated data should be used in the simulation. The chloride concentration was determined by the acid-soluble method. The examined concrete surface would not be smoothed off again. The similar surface roughness nearby the previous examination was selected to each alternative investigation. Each data was examined the total surface chloride content during June to September of rainy season especially after typhoon periods in 2003. The amount of rain during the examination is shown in **Fig.7**. Besides, the wind ratio in the 16 directions during April to September is divided as shown in **Fig.8**.

(3) Results and discussion

Kochi Prefecture has the shoreline connecting to the Pacific Ocean whereas the airborne chlorides are transported to concrete surfaces, mostly in the storm. Kochi Prefecture coastline is faced to the southern wind which is the transportation path of typhoons. The front-side of stairs concrete facing to the ocean was examined in both normal and rough surface. The stairs structure does not have smooth surface because of the long-term erosion by rainfall. Again, another side which is perpendicular to the front-side and facing to the eastern wind was also investigated in the effect of the wind direction. The Amedas weather information in **Figs.7 to 8** is applied to analyze with the examined data. The experimental results were computed by the average of the chloride contents of 5 layers, which each layer does not show much different$^{14)}$. In order to notify the surface chloride change by rain, the data from two locations were separately plotted on the examination date which is illustrated in **Figs. 9 to 10.**

The experimental results were defined as the apparent amount of surface chloride content while flux of chloride ions in concrete is continuing. The experimental results are necessary merely for understanding the influence from rain. In **Fig.9**, the acquisition of total surface chloride content of an outdoor structure is not constant. It is proved that the rain affects the dissolution of some surface chloride contents. After the surface is saturated, the speed of surface chloride dissolution is assumed constantly.

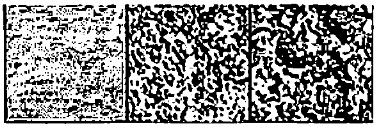

Fig.6 Three differences on the investigated surface roughnesses of "smooth", "normal", "rough", respectively

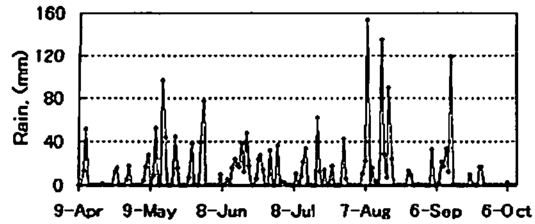

Fig.7 Raining period during April to September in 2003

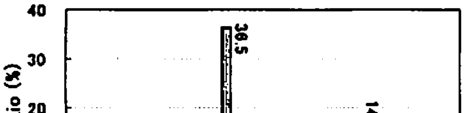

Fig.8 Ratio of 16 wind directions during April to September in 2003

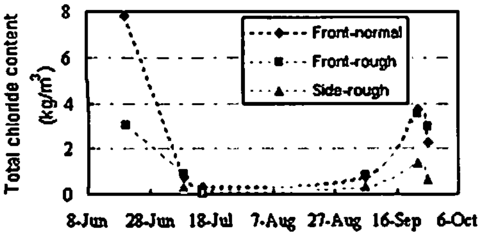

Fig.9 Investigated chloride contents of stair concrete surface along Maehama shoreline in Kochi Prefecture

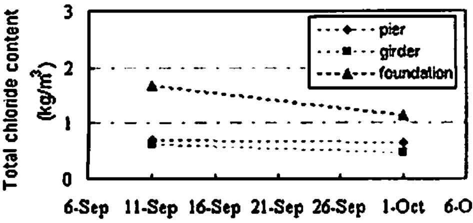

Fig.10 Investigated chloride content on bridge concrete surface at 100m from shoreline in Yatsu, Kochi Prefecture

According to the raining behavior in Japan, it is precipitated diminutively for entire day. Thus, the concrete surface is kept saturated, and then the chloride ions are continuously expelled.

Subsequently after raining, winds begin to substantially accumulate surface chlorides. Explicitly, the windy atmosphere after typhoon proceeded at that location cause highly accumulation. The coefficient of cumulative surface chloride is high in rough surface due to the greater specific surface area. Simultaneously, rain also affects to the chloride dissolution, tremendously. The increment of surface chloride content is started again after the ending of rain. The saturated surface is considered to be a higher capability to adsorb airborne chloride than that in drying period. Hence, the fluctuation of surface chloride seems to be widely ranged. It is also able to mention that the surface chloride content of outdoor structures might be null after ending of rainy season.

In **Fig. 10**, the bridge structural members across the mouth of the river at 100m far away from shoreline were observed. It had been constructed in August, 2001. A partial abutment of this structure is exposed outside subjecting with the influence of rain. It is a non-structural member which has low strength. The box girder with an inclined slope is exposed to low effect of rain. The pier is located indoor without the effect from rain entirely. All surfaces are noted that they are in the smooth condition. The surface chloride contents for indoor structures are absolutely not removed by rainfall, unless the rain drainage path would not run over them. During three weeks between two observations, the smooth surface has a small accumulation of chloride content. Contrasting the surface chloride contents between outdoor and indoor structures, their accumulations have the different propensity. The erosion of structural surfaces governs the degree of airborne chloride accumulation. The surface chloride content for structures should be treated appropriately because it is concerned with the amount of chloride ingression. Thus, a computational model of chloride ingression in porous concrete, which is able to solve this problem, is involved.

3. COMPUTATIONAL APPROACH FOR TOTAL CHLORIDE DISTRIBUTION IN CONCRETE

(1) General

A new proceeding of chloride attack on concrete structures was proposed by Swatekititham[15] for structural located in land. This computational model was presented as the series of three models. First is the estimation of airborne chlorides and the transport mechanism. Second is the estimation of surface chloride boundary condition throughout the structural life. Third is the chloride ion ingression through the depth of concrete. Finally, the chloride profile in concrete at the structural lifetime is obtained. DuCOM11),12) is the appropriate model for calculating the chloride distribution in actual concrete structure. The governing equations in DuCOM by advective-diffusive phenomenon12) with time dependent are implemented as expressed;

$$\partial(\phi S.C_{cl})/\partial t + divJ_{cl} - Q_{cl} = 0 \qquad (3)$$

$$J_{cl} = (-\phi S.D_{cl.} \nabla C_{cl}/\Omega) + \phi S.u.C_{cl} \qquad (4)$$

where, ϕ is porosity, S is degree of saturation, C_{cl} is concentration of chloride ion(mol/l), J_{cl} is flux of chloride ion (mol/m^2.s), Q_{cl} is the reduction of free chloride, D_{cl} is chloride ion diffusivity in pore solution phase (m^2/s), u is the averaged velocity of pore water and Ω is tortuosity of pore $(\pi/2)^2$.

For the completion of the calculation, the time-scaled boundary chloride content and environmental conditions must be fulfilled. The surface chloride content inputted in this program has different meaning of surface chloride content from the observation. The examined surface chloride content of a real structure is the apparent value after the advection-diffusion through concrete depth. For DuCOM, the surface chloride content is the ideal concentration before taking an action of the advection-diffusion. For example; in the same period of time, the amount of airborne chlorides reaching structural surfaces is equivalent to the total chloride concentration in concrete after this ideal value taken an effect of the advection-diffusion. This is cautious to avoid a wrong interpretation on the simulation.

(2) Prediction on ideal surface chloride content, C_o

The computation of the ideal surface chloride content prior to the advection-diffusion was simply proposed in a constant value in a wind speed. The coefficients of surface chloride increment are proposed in two different surface roughness at wind speed 3m/s. These coefficients are set as the reference illustrated below;

- Increment of C_o at wind speed = 3 m/s
  Rough surface = 0.018 kg/m^3 per hour
  Normal surface = 0.013 kg/m^3 per hour

In fact, the increment of surface chloride content is based on the numbers of airborne chloride which are transported to the structural surface. The average airborne chloride content was simulated by the theory of the particle equilibrium of force including drag of air16). Following this model, the empirical formula17) was established using the Amedas wind speed which the measuring point is loacated a certain distance from seashore. Slower speed, farther distance due to obstacles and landscape is generally observed by Amedas. Therefore, the average 10-m wind speed is much suitable for the analysis rather than the Amedas wind speed. The coefficient should be calibrated from 0.35 to 0.02 due to the change of wind data, and expressed as follows;

$$C_{air,hr} = 0.02 r_{wind}.U^3.(X'+10)^{-0.5} \qquad (5)$$

where, $C_{air,hr}$ is the airborne chlorides per hour (mg/dm^2/hr), U is the averaged 10-m wind speed at the seashore (m/s), X' is wind-transported distance from seashore (m), r_{wind} is 1.0 in case of the efficient wind direction or otherwise 0. The efficient wind direction means a wind direction which can transport the airborne chloride from sea to the surface of structures. For the different wind speed, the proportional between wind speed and amount of C_o is proposed by the third power of wind as shown below;

$$C_o = C_{o(3m/s)} \frac{C_{air,hr}}{C_{air,hr(3m/s)}} \qquad (6)$$

where, C_o is the increasing of surface chloride content at a wind speed per hour, and $C_{o(3m/s)}$ is the reference of surface chloride increment per hour whereas wind speed is equivalent to 3m/s.

Considering the effect of wind directions on airborne chlorides transportation, the effective wind direction defines as wind with perpendicular to the structure surface in the shortest transporting distance. The common efficient wind directions are in the angles of ±67.5°, but it might be less due to the particular coastal panorama. The different wind directions impact on a longer distance of transportation expressed as

$$X' = X / \cos\varphi \qquad (7)$$

where, X is distance from seashore in effective wind (m), and φ is deviated angle from the effective wind direction.

An efficient wind direction brings numbers of airborne chlorides to a structure. The surface chloride content is increased by the cumulative airborne chloride on that surface. During an inefficient wind direction, the accumulative surface chloride is kept constantly due to lack of airborne chloride on the scene. During raining period, the airborne chlorides in the atmosphere are assumed to be totally dissolved with the precipitation. This means that none of airborne chloride appears on the surface of indoor structures during precipitation. For outdoor structures, rainfall is run over the surface and then removes some existing surface chloride content. The explicit conception between the amount of rain and surface chloride deduction are not existed. It is very complicate to derive the relationship among the amount of precipitation, duration and surface chlorides removal. In this paper, a simplified coefficient is recommended constantly in daily action. This proposal is regarded as the raining behavior in Japan as mentioned in **Section 2.(3)**. The coefficients of two different roughnesses are illustrated as follows;

- Removal of C_o by Raining

Rough surface	= 0.650	kg/m^3 per day
Normal surface	= 0.450	kg/m^3 per day

The estimation of surface chloride content in any environmental circumstances was successful in this paper. The localized ambient environmental conditions by JMA were incorporated with the calculation of the surface chloride distribution within one year. The environmental conditions of wind and rain during 1998-1999 were appealed with the cumulative surface chloride. The calculation was started from autumn in 1998 to the rainy season in 1999. This pattern was concluded that the surface chloride content of an outdoor structure is null after rainy season[14]. This statement was described by the effect of high raining periods (days) dissolving the surface chloride content. Three outdoor revetments at the seashore of Ishikawa, Ehime, and Yamagata Prefectures were simulated. The results of surface chloride distribution in a 1-year cycle were illustrated in **Figs. 12 to 14** (left).

(3) Computational chloride distribution in concrete structure

In **Fig.11**, the structures which are located in the submerged and tidal zones are subjected directly to the sea-salt ingression. The chloride ingression was simulated based on the flux from the sea chloride concentration (1stzone) by diffusion, advection and quasi-adsorption behaviors[12),18)]. However, the simulation of chloride ingress for the structures located on land is totally different from those structures as mentioned before. The surface condition is not saturated for all the time and the surface chloride content is inconsistent. Thus, the chloride content on concrete surface (2ndzone) is rather represented as the boundary condition for flux of chloride ingression. Flux of quasi-adsorption is occurred only when structure are submerged in the seawater. Thus, the surface condensation due to quasi-adsorption was ignored. It is cautioned that only free chlorides on the surface are able to penetrate through the pore structure in concrete. Hence, the fixed chloride content on concrete surface was omitted. The free chloride concentration (C_{cl}) in the pore structure is computed by

$$C_{cl} = 1000\, C_o(1-\alpha_{fixed}) \,/\, [M_{cl}\cdot V_{pore}\cdot S] \qquad (8)$$

$$\alpha_{fixed} = \begin{cases} 1.0 & C_{tot} \le 0.1 \\ 1-0.35(C_{tot}-0.1)^{0.25} & 0.1 \le C_{tot} \le 3.0 \\ 0.543 & 3.0 \le C_{tot} \end{cases} \qquad (9)$$

where, C_{cl} is free chloride concentration in pore solution (mol/l) at time t_i, C_o is total chloride concentration (kg/m^3) at time t_i, C_{tot} is total chloride concentration (% by weight of cement) at time t_i, M_{cl} is molecular weight of chloride (35.5g/mol), V_{pore} is pore volume (l/m^3) of a concrete at time t_i, S is degree of saturation at time t_i [saturated condition, S is 1.0], and α_{fixed} is the fixed chlorides at time t_i[18)].

Inputted by ambient Cl$^-$ concentration (1) → surface free Cl$^-$ content (2)

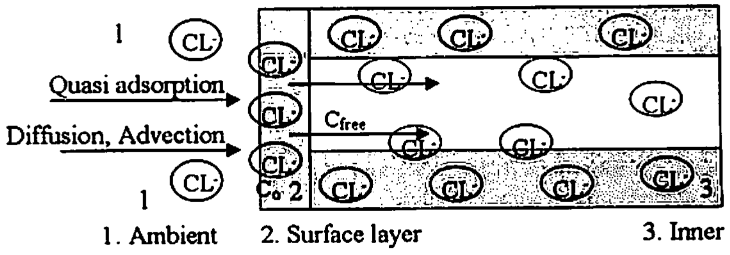

Fig.11 Chloride transport mechanism in concrete structures [Zone 1: ambient layer, Zone 2: surface layer, Zone 3: inner layer]

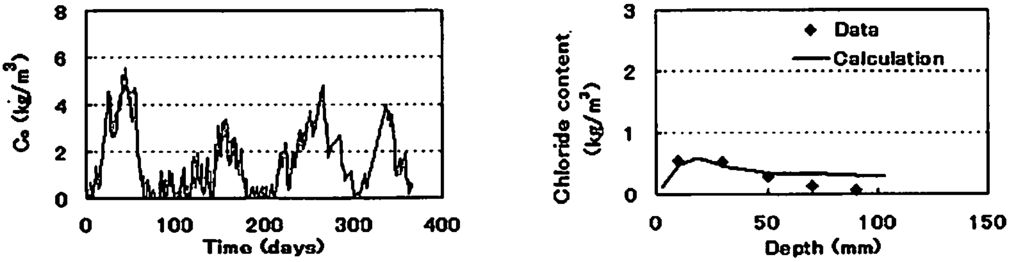

Fig.12 1-year cycle of the surface chloride content and computed result for the investigated data in Ishikawa Prefecture

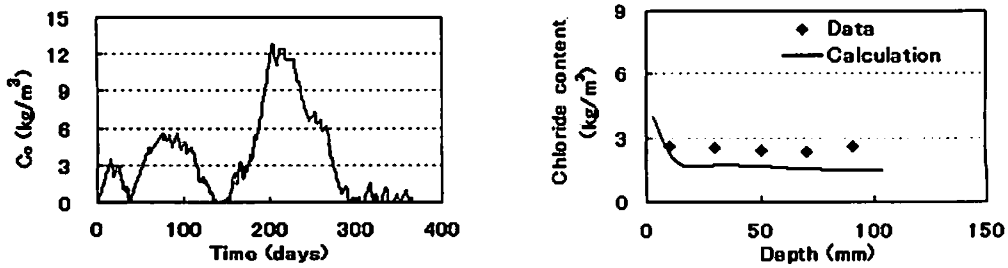

Fig.13 1-year cycle of the surface chloride content and computed result for the investigated data in Ehime Prefecture

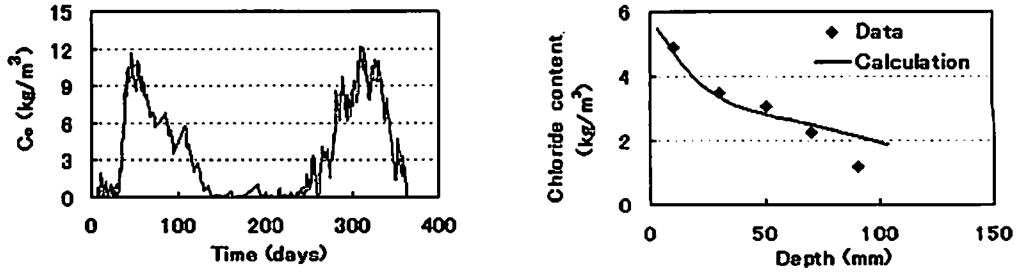

Fig.14 1-year cycle of the surface chloride content and computed result for the investigated data in Yamagata Prefecture

Table 2 Annually-averaged wind condition in 1998-1999

Locations	Annual Wind speed (m/s)	Annual Efficient Wind directions (%)
Ishikawa	3.4	25
Ehime	3.7	32
Yamagata	4.5	47

The wind conditions of these three samples are shown in Table 2. The rainy days in Ishikawa and Ehime Prefectures are similar about 110 days per year, but they are higher in Yamagata Prefecture at 150 days per year. They were counted on the day which had the precipitation more than 2mm. However, the location of this Prefecture is located along the northern part of the Japan Sea coastline and affected by vigorous windy condition in winter. This environment provides a large amount of airborne chlorides to recompense the dissipation of surface chloride content. This could be concluded that wind speed, wind direction and rain create a variety of surface chloride distribution. The free chloride distribution in surface porosity for 1-year cycle was established for each particular sample. Finally, the simulation of chloride ingression for a structure was iterated up to its lifetime.

The computational results of the chloride distribution in concrete are compared with the observed data as illustrated in **Figs.12 to 14**. The variety of chloride distributions are referred to the exposure time, concrete property and localized environmental condition. The surface chloride distributions of three samples would not reach the level of 9kg/m^3, recommended by JSCE specification, 2002. However, these results are shown precise calculated results comparing with the observed data. In addition, these are also the main reasons to explain the scattering plots of surface chloride contents illustrated in **Fig.5**.

4. CONCLUSIONS

(1) The structures constructed nearby the seashore might not always have a large amount of the chloride distribution in concrete due to the rainy period which influences on the removal of surface chloride content.

(2) The structures subjecting to the rainfall were eroded and changed into rougher surface, which caused a larger specific surface area to addict the airborne chlorides. However, the dissolution of surface chloride content due to rain was also large as well.

(3) The condensation due to quasi-adsorption on concrete surface is excluded in the chloride ingression, where the structures are not exposed directly to the sea water.

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