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EVALUATION OF PARAMETERS EFFECTING CHLORIDE INDUCED DETERIORATION BASED ON ACTUAL DATA IN SITU

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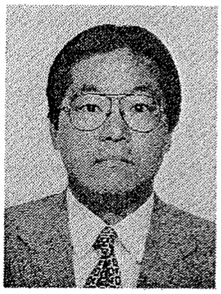
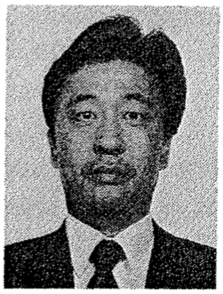

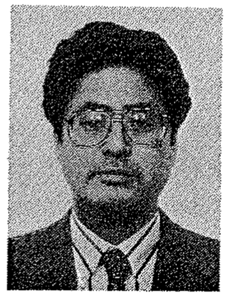

Tomoaki TSUTSUMI Shinichi SHIRAI Noboru YASUDA Manabu MATSUSHIMA

To accurately evaluate chloride induced deterioration, consideration must be given to the effects of regional differences, the locations of structures and other variables in addition to actual structure deterioration data. Deterioration data accumulated over more than 20 years concerning reinforced concrete structures within Tokyo Bay was collected and analyzed, then applied to a quantitative study of factors governing the surface chloride ion density, the diffusion coefficient, and the reinforcement corrosion rates: important parameters in chloride induced deterioration.

Keywords: diffusion coefficient, chloride ion density, data analysis, sampling data in situ, reinforcement corrosion speed

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1.INTRODUCTION

More than a decade has passed since the problem of rapid deterioration of concrete structures in marine environments first began to attract attention.[1] During those years, researchers in various fields have been studying the problem earnestly, performing quantitative analyses of chloride ion diffusion in concrete and the period when reinforcement begins to corrode. The Japan Society of Civil Engineering[2] and the Japan Concrete Institute[3] have already proposed durability design methods based on the results of this study. However there are still issues to be resolved concerning the setting of the various coefficients needed to apply these methods. Because chloride induced deterioration of structures is influenced substantially by regional differences and the location of each structure, in order to accurately evaluate the deterioration phenomenon of a particular structure, deterioration data for its location must be considered. However in fact, because of the lack of or, poor maintenance of, data concerning actual structures, most evaluations are based on laboratory tests or short term exposure experiments. Chloride induced deterioration data for actual structures includes the results of a detailed survey of chloride ion content, the natural electrical potential of reinforcement, etc. conducted by Otsuki et. al.[4] at 16 facilities in 11 harbors throughout Japan. Takewaka et. al.[5] performed qualitative evaluations of the chloride ion diffusion process based on the results of marine exposure experiments or studies of actual structures performed by research institutes throughout Japan. However there are few reports involving the analysis of deterioration data by installation location and structure category limited to a single region and a study of the degree of the effects of these factors based on this analysis.

This study, concerning factors influencing chloride induced deterioration in Tokyo Bay, was performed by collecting, organizing, and analyzing inspection and repair records accumulated over more than 20 years for RC structures, including landing piers for petroleum and coal and revetments, constructed along the seashore of Tokyo Bay. In line with earlier research[6], the chloride induced deterioration process was categorized as the incubation period up to the point where reinforcement is started by the diffusion of chloride ions and the development period which begins with reinforcement corrosion followed by the appearance of cracks in the reinforcement axially caused by pressure from the expansion of the reinforcement. The governing parameters during the incubation period are the surface chloride ion density and its diffusion coefficient, while the governing parameter during the development period is the reinforcement corrosion speed. This study was a qualitative study of factors influencing these parameters.

2. FACTORS INFLUENCING CHLORIDE INDUCED DETERIORATION

2.1 Factors Influencing Chloride Ion Diffusion

Generally, chloride ion diffusion is, as a diffusion phenomena conforming to the concentration slope, evaluated by Fick's diffusion equation as shown in Eq.(1).

$$C_C(x,t) = C_0\left\{1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_C \cdot t}}\right)\right\} \tag{1}$$

Where:

$C_c(x,t)$: Chloride ion density in concrete at a depth from the concrete surface x at time t from the beginning of diffusion. (kg/m^3)

C_0: Chloride ion density on the concrete surface (kg/m^3)

erf(): Error function.

D_c: Equivalent diffusion coefficient of chloride ions. (cm^2/sec)

x: Depth from the concrete surface. (cm)

It is possible to represent the chloride diffusion process based on the equivalent diffusion coefficient D_c and the surface chloride ion density C_0 in Eq.(1). These values, namely the equivalent diffusion coefficient and the surface chloride ion density, are believed to vary according to environmental conditions, the concrete quality, etc. For this reason, attempts have been made to clarify the characteristics of the factors which govern the equivalent diffusion coefficient and the surface chloride ion density.[7] Figure 1 presents the relationships between factors influencing the diffusion of chloride ions. As it shows, the equivalent diffusion coefficient is influenced by mix proportion factors such as cement type, casting method and other execution conditions. The surface chloride ion density is governed primarily by environmental conditions: distance from the sea and so on. Many researchers have pointed out that the equivalent diffusion coefficient and the surface chloride ion density are effected by mix proportion conditions, execution conditions, and by environmental conditions,[8] but many of these studies are limited to laboratory tests and outdoor exposure experiments, and there are relatively few study results of actual structures. While it is difficult to prepare exposure experiment specimens which reflect any execution effects and most parts of exposure experiment specimens are in sound condition, actual structures are frequently deformed by fine cracks and stripping caused by continuous load. Therefore, data from studies of actual structures reflect conditions different from those present during exposure experiments. In many cases, the lack of any clear information concerning the concrete mix proportion or execution conditions of an existing structure is a genuine problem. Also, it is often difficult to evaluate the surface chloride ion density and the equivalent diffusion coefficient under the mix proportion and execution conditions shown in Figure 1. Therefore, for this study, five items which can actually be evaluated, as shown below, were set as influential factors in place of mix proportion or execution conditions, and a study was performed of their relationship with the surface chloride ion density and the equivalent diffusion coefficient. In addition to structure location data, data considered during this study included splash zone data from Tokyo Bay, a region marked by a harsh salt damage environment, and one which is well documented.

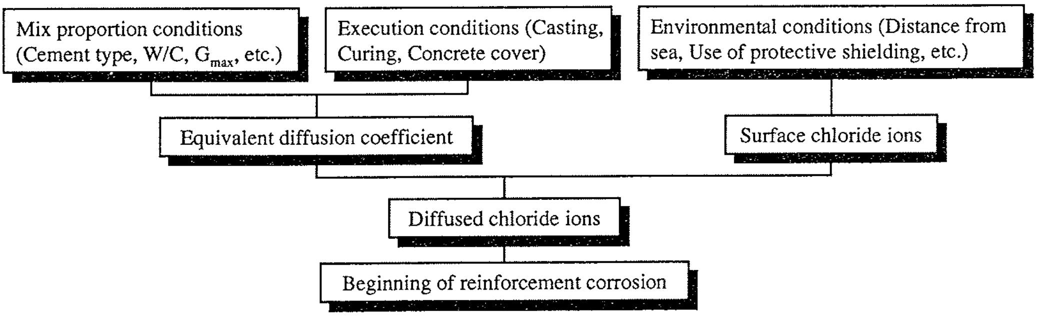

Figure 1. Relationships of factors influencing the diffusion of chloride ions.

(1) Structure Installation Location

Takeda et. al.[9] exposed specimens in a splash zone, and both under the surface and in the air above the surface of the ocean to measure chloride ion diffusion. These tests revealed that the surface chloride ion density on the specimens was highest for those to the splash zone, less for those exposed under the surface of the ocean, and least for those in the air above the surface. The installation location of structures is categorized as shown in Figure 2.

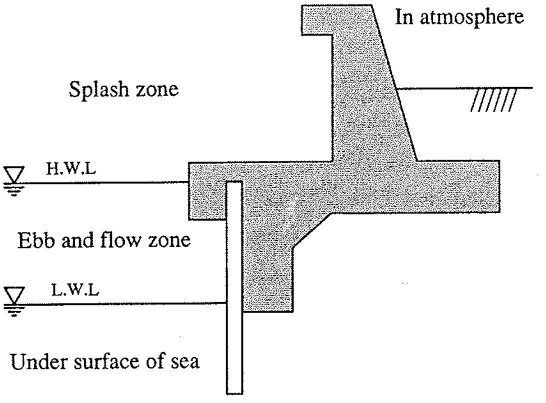

Figure 2. Location of structure.

(2) Member Categories

Concrete structures can basically be classified into beams, columns, walls, and slabs. A survey of prestressed concrete beam deterioration performed by the former National Railway Company revealed large surface chloride ion density on the bottom surfaces of beams, but only a few on the bottom surfaces of slabs.[10] This study referred to these results to determine the categorization shown in Figure 3: one based on shape of member and installation location. Beams and columns are not differentiated because it is assumed that columns, being located below deck slabs and beams of bridges, are exposed to sea water splash conditions as severe as those which effect beams. because there are differences in the way that surfaces of walls and slabs are washed by rain water, essentially they should be in different categories. However, because it would have been difficult to distinguish between the two using the data provided for this study, data for the two members, which have similar simple shapes, is combined, despite the lack of precision of this approach. To eliminate the effects of wind direction, when analyzing the material, only data for members located in the same direction towards the seashore was included.

(3) Location of Member Surfaces

Surface chloride ion density is governed by the extent to which the member is exposed to flying salt water splash. Although conducted not in the same region where the data for this study was obtained, Kashino et. al. [10], measured flying chloride ions in the atmosphere above solid land, discovering that the difference in the chloride ion density adhering to parts protected from the spray by shielding was about 1:0.4 within 100 m of the ocean. Therefore, both the surfaces on the seashore side and opposite side (below referred to as rear side) of structures were studied. However, because most of the structures targeted by this study are port facilities, all sides of beams and columns were located in splash zones. Consequently, because it is difficult to distinguish from the seashore side and rear side of structures, their effect is excluded from this study. As in the member category case, to

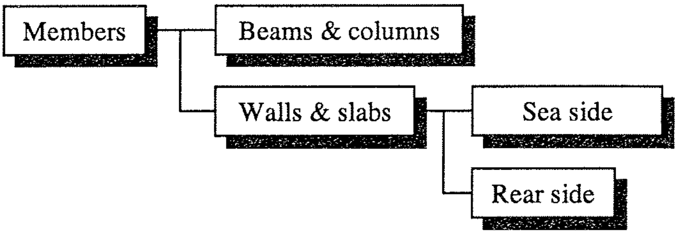

Figure 3. Member and member surface categories.

eliminate the effects of wind direction on this factor, the study categorized the walls and slabs as seashore side and rear side. Walls and slabs are categorized as shown in Figure 3.

(4) Compressive Strength

Based on laboratory experiments, one of the authors[11] represents the chloride ion diffusion properties as the corrosion current value to obtain a negative correlation with the compressive strength. It is known that compressive strength is described by a function of the water cement ratio, and the diffusion properties of chlorides are also influenced by the water cement ratio.[7] Therefore, in this study, compressive strength was considered a factor which substitutes for the water cement ratio, and its relationship with the equivalent diffusion coefficient was studied.

(5) Dominant Wind Direction

Kashino et. al.[10] studied the effects of the dominant wind direction on chloride ion spray in City S, reporting that the dominant wind direction had little effect on chloride ion spray, but that sea breezes, which blew in one direction at night and the opposite during the day, do have a great effect. In order to study the effects of the dominant wind direction on marine structures in Tokyo Bay, the relationship between dominant wind direction and location of structures was considered under three categories as shown in Figure 4. And because this factor is assumed to influence the surface chloride ion density, its effects on the equivalent diffusion coefficient were not examined.

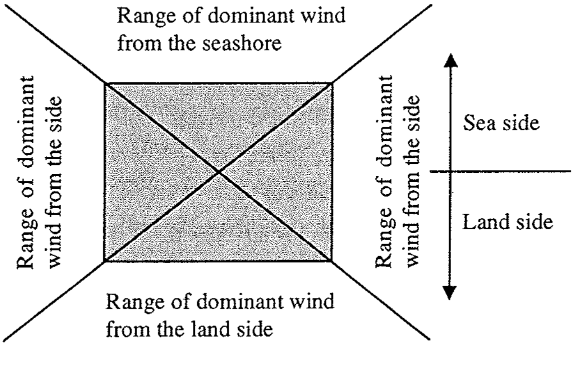

Figure 4. Relationship between structure and dominant wind direction.

2.2 Factors Influencing Reinforcement Corrosion Speed

Reinforcement corrosion speed is an important parameter used to estimate when cracking will appear. However as shown in Figure 5, corrosion speed is influenced in complex ways by a range of factors including the oxygen and water content ratio around the reinforcement, governed by the concrete mix proportion and environmental conditions, the reinforcement stress produced by the loads acting on it, and variables other factors. Under present circumstances, efforts to formulate the situation are only done under limited conditions. For example, Seki et. al.[12] have proposed a method in which the form of reinforcement corrosion is assumed to be under cathode control, and the corrosion speed is formulated based on the law of conservation of mass of the dissolved oxygen around the reinforcement. Yokozeki et. al.[13] developed an estimation equation for corrosion speed which assumes that all the oxygen around the reinforcement is consumed by the corrosion production process. These are both theoretical studies under limited conditions; not evaluations of the corrosion speed of actual structures.

This study not only evaluated corrosion speed; it focused on the reinforcement corrosion value to evaluate the corrosion speed from the relationship of the corrosion value with elapsed time. The following three items were assumed as factors influencing the reinforcement corrosion.

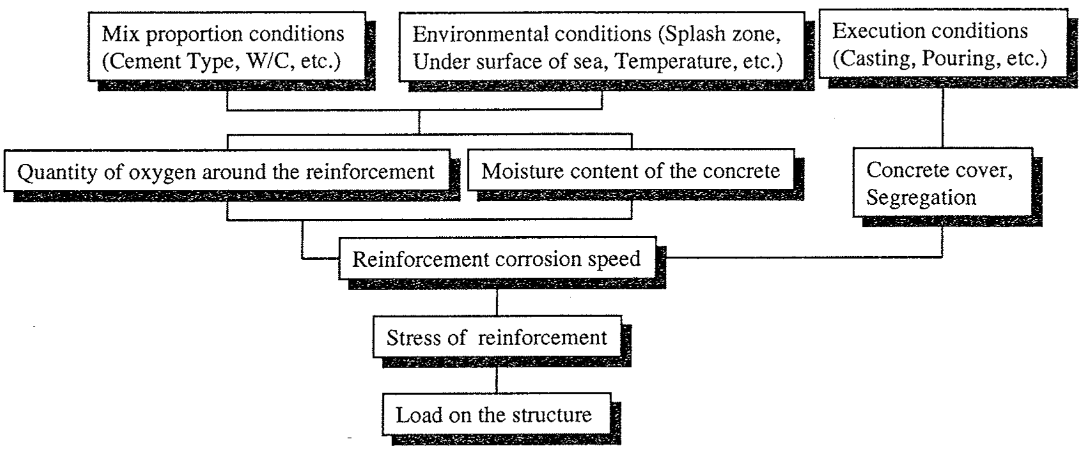

Figure 5. Factors influencing reinforcement corrosion speed.

(1) Concrete Cover Thickness

Morinaga et. al.[14] have reported that the results of deterioration surveyed at drainage channels of thermal power plants show that corrosion cracking appeared where the concrete cover was 60 mm or less, and that it was particularly severe where the concrete cover thickness was 30 mm or less. This suggests that even where elapsed years and the diffusion coefficient are identical, differences in the concrete cover thickness cause differences in the time required for the chlorides to reach on the reinforcement, with the result that corrosion begins at different times.

(2) Elapsed Years

Reinforcement corrodes when there are sufficient supplies of oxygen and water. Therefore, when stable supplies of both are provided, the corrosion value is estimated to rise as years pass.

(3) Other Influential Factors

Reinforcement corrosion speed is, in addition to the above factors, also influenced by the member category and its compressive strength. When comparisons of different kinds of members are made after the same number of years, it is estimated that even when the concrete quality and the concrete cover are identical, differences in the surface chloride ion density will result in differences in the corrosion value. Compressive strength is described by a function of the water cement ratio, and the smaller the water cement ratio, the greater the nominal resistance of the concrete. For this reason, it is estimated that the greater the compressive strength, the higher the specific resistance and the smaller the corrosion value.

3.ANALYSIS RESULTS

3.1 Surface Chloride Ion Density and Equivalent Diffusion Coefficient

Maintenance engineers for existing concrete structures have to supplement daily inspections of the structures with periodical inspections performed once every six months to determine if repair work is necessary. If necessary, this includes the extraction of a concrete core. The data used for this study included diffusion coefficient and surface chloride ion density data obtained from the density distribution of chloride ions in the depth direction of concrete cores obtained during such inspections. The chloride ion density data used in this paper was obtained using the method of potentiometric titration.

(1) Structure Installation Location

Figure 6 shows the distribution of surface chloride ion density. Although the surface chloride ion density tends to be higher under the surface of the sea and in tidal zone than it is in the splash zone, there is insufficient data to permit a clear theory regarding these tendencies.

(2) Member Category

Figure 7 shows the distribution of surface chloride ion density and Figure 8 shows the distribution of the equivalent diffusion coefficient. Assuming that data actually measured in-situ represents the state of the structure's concrete, basically, the data obtained should be used without modification. But, because it includes data considered idiosyncratic, featuring severe localized deformation, the method proposed by Grubbs [15] was used to dismiss abnormal data. The dismissal limit values obtained were n=26 for the surface chloride ion density, n = 27 for the equivalent diffusion coefficient, and 5% for the significance level. Both figures reveal a great difference between the surface chloride ion density, which ranges from 1.0 kg/m^3 to 21.0 kg/m^3. And while there is less data for walls than for beams, the distribution range is identical for both members.

Although data for the equivalent diffusion coefficient of beams and walls varies, their distributions are almost identical, with both distributed between 1.0×10^{-8} and $1.0\times10^{-7}cm^2/sec$. This coincides closely with the survey results of landing piers obtained by Otsuki et. al.[4] A W-examination[16] was performed to determine whether the data within the range of this survey should be clearly categorized based on member category or whether it is within the range of simple scattering. The level of significance of the test was set at 5%. The results are shown in Table 1. This table reveals that the surface chloride ion density and equivalent diffusion coefficient were part of the same population in the case of both walls and beams, leading to the conclusion that the member category is not influential.

Table 1. Results of W Examination

Null hypothesis	Alternative hypothesis	Number of data		Results
		m	n	
Surface chloride ion density on beams and walls in the same population	Smaller surface chloride ion density on walls	5	21	Null hypothesis
Equivalent diffusion coefficient for beams and walls in the same population	Lower equivalent diffusion coefficient on walls	9	18	Null hypothesis

Note) Data number m: Data indicating the null hypothesis. n: Data in another direction

One of the authors[17] has analyzed a survey of the deterioration of concrete bridges near the ocean throughout Japan by the Ministry of Construction, indicating that along the Japan Sea coast where environmental conditions are harsh, differences in composition between members influenced the surface chloride ion density. However the effects of member categories were not observed in the results of this study. This difference is a result of the fact that structures in Tokyo Bay are exposed to relatively less severe environmental conditions, and the reasons for the differences lie in scattering of the data.

(3) Location of Member Surfaces

Figure 9 shows the distribution of surface chloride ion density, while Figure 10 shows the distribution of equivalent diffusion coefficients. Despite considerable scattering of the surface chloride ion density, there are differences in the distribution ranges obtained for the seaside and the rear side; with more surface chloride ions observed on the seaside than the rear side. The seaside/rear side ratio is 1: 0.6. The ranges of the equivalent diffusion coefficient data on the seashore and rear sides are almost identical, with the distribution pattern represented by a lognormal distribution. As in the case of concrete specimens used for laboratory tests, if there were no cracks or other defects, scattering of the equivalent diffusion coefficient was limited to scattering at the time the specimens were prepared and had a normal distribution, but within the range of this data, it was a lognormal distribution. This is a result of the fact that actual structure data includes larger values as a result of execution scattering, fine cracks or other defects.

(4) Compressive Strength

Figure 11 presents the relationship between compressive strength and equivalent diffusion coefficient. The specimens used for compressive strength were taken close to the specimens used for the diffusion coefficient measurements. As the same figure shows, the measured values are widely scattered and there is no clear correlation between the compressive strength and the equivalent diffusion coefficient. Laboratory tests performed by one of the authors[11] has revealed a negative correlation between the compressive strength and equivalent diffusion coefficient, but the study results of actual structures have not shown as clear a relationship as that revealed by the results of laboratory tests. There are a number of reasons for this discrepancy. The structures studied have been in use for more than 20 years, fine cracking has likely occurred under the service load on the structures, the structures covered by the data differ, and the effects of variances in construction quality are dominant.

(5) Dominant Wind Direction

Figure 12 shows the distribution of surface chloride ion density. Here, the dominant wind direction is set based on year-round data obtained from wind vanes and anemometers installed near the structures. This figure shows that the distribution range of the data is almost identical on the seaside, sides at right angles to the seashore, and from the mountainside, indicating that it is not effected by the dominant wind direction. This is because the data was obtained inside Tokyo Bay, where the dominant wind direction, being less dominant than it is along the Japan Sea in Hokuriku and Tohoku, showed no effect.

(6) Surface Chloride Ion Density and Equivalent Diffusion Coefficient in Tokyo Bay

Before the above results were summarized, beam members were analyzed in order to study the characteristics of the relationship between surface chloride ion density and elapsed years. The results are presented in Figure 13. This figure shows that although there is scattering and bias in the data, no clear relationship with elapsed years is evident. Based on the above study results, the surface chloride ion density was limited to splash zone and to seaside data, while the equivalent diffusion coefficient was limited to splash zone data to summarize the distribution of the surface chloride ion density and the equivalent diffusion coefficient of reinforced concrete structures in Tokyo Bay. The results are shown in Figures 14 and 15 respectively. The results of an χ-square test show that a normal distribution is appropriate for the surface chloride ion density and a lognormal distribution is suitable for the equivalent diffusion coefficient. This is because while the surface chloride ion density is influenced by the environment where the structure stands, the equivalent diffusion coefficient is, as stated above, influenced by data including latent defects in the concrete, and high value data is dominant. The distribution for the surface chloride ion density is a maximum value of 24.3 kg/m^3, minimum value of 0.14 kg/m^3, mean value of 8.84 $kg/m^3$with a standard deviation of 5.78 kg/m^3 (obtained using 67 data). The distribution for the equivalent diffusion coefficient is a maximum value of 7.52×10^{-8} cm^2/sec, minimum value of 1.48×10^{-9} cm^2/sec, mean value of 1.73×10^{-8} cm^2/sec with a standard deviation of 1.59×10^{-8} cm^2/sec (obtained using 66 data).

3.2 Reinforcement Corrosion Speed

In this paper, reinforcement corrosion speed C_s was evaluated as the cross section reduction speed obtained by dividing the reinforcement corrosion rates as defined by Eq. (2) by the elapsed years.

$$C_S = \frac{\Delta_r}{T} = \frac{1 - A_d/A_S}{T} \tag{2}$$

Where:

Δ_r: Reinforcement cross section corrosion rates (%)

A_d: Cross section area of corroded reinforcement obtained from the reinforcement diameter measured with a vernier micrometer. (cm^2)

A_s: Nominal cross section area (cm^2)

T: Elapsed years (number)

Before analyzing the data, data for members with concrete cover thicknesses less than 25 mm or greater than 150 mm were eliminated from this study.

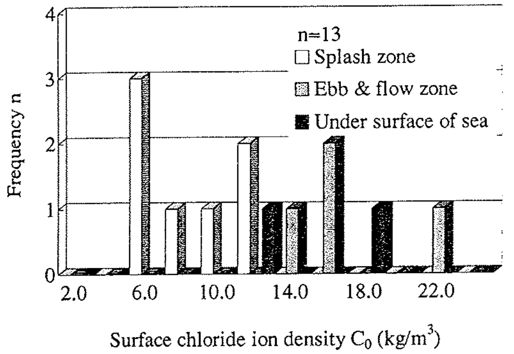

Figure 6. Surface chloride ion density.

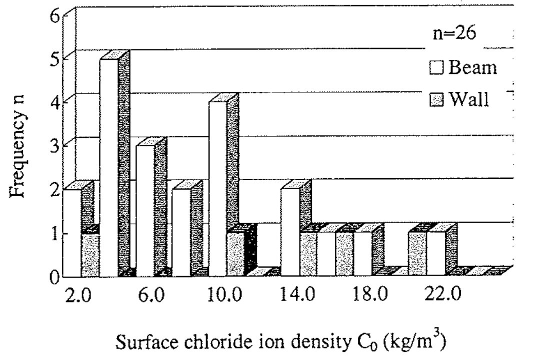

Figure 7. Surface chloride ion density.

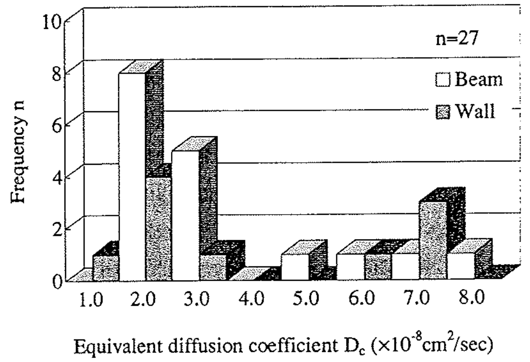

Figure 8. Equivalent diffusion coefficient.

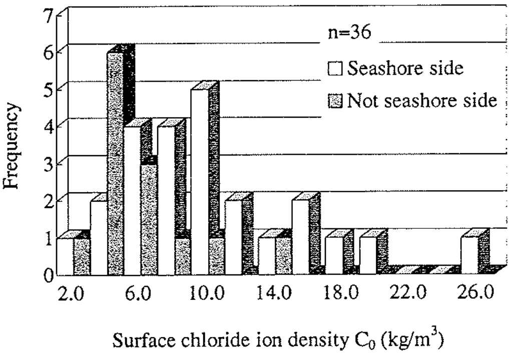

Figure 9. Surface chloride ion density.

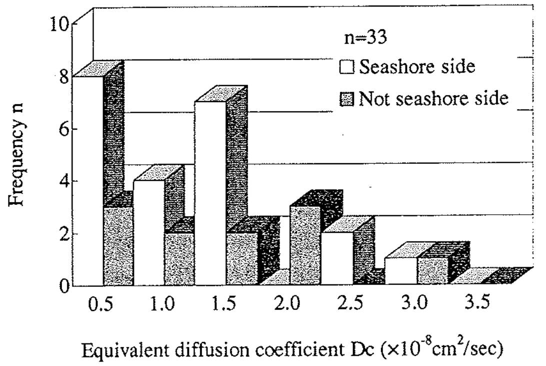

Figure 10. Equivalent diffusion coefficient.

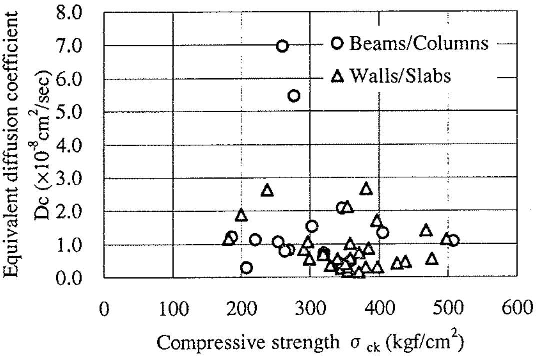

Figure 11. Relationship between compressive strength and equivalent diffusion coefficient.

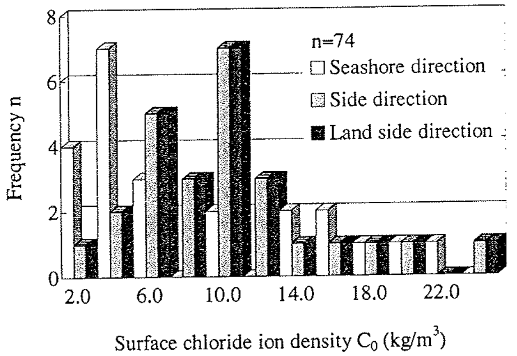

Figure 12. Surface chloride ion density.

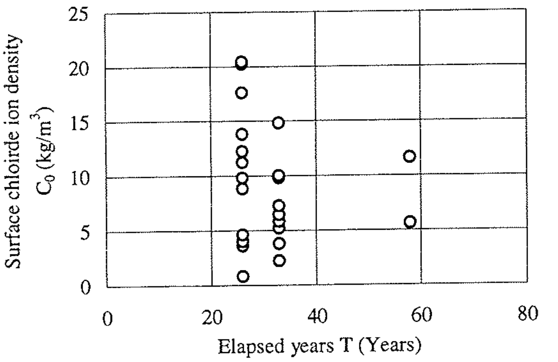

Figure 13. Relationship between surface chloride ion density and elapsed years.

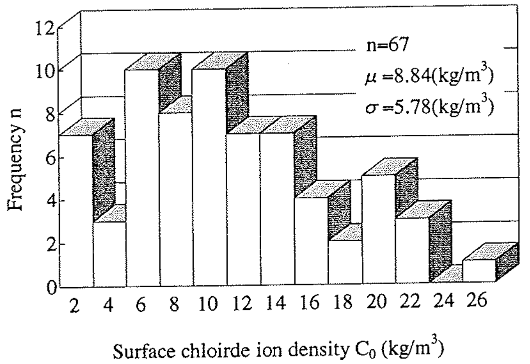

Figure 14. Surface chloride ion density.

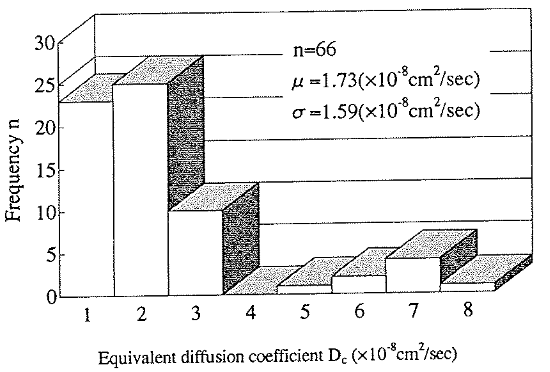

Figure 15. Equivalent diffusion coefficient.

(1) Effects of Reinforcement Diameter

Essentially, the reinforcement corrosion speed should be evaluated based on the annual cross section reduction, but the evaluation was based on the reduction rates because much of the survey data used was reported as the reduction rates observed from Eq.(2). By performing evaluations based on the reduction rates, it was observed that the greater the reinforcement diameter, the faster the reinforcement corrosion speeds, even at identical reduction rates. Therefore, a relationship between reinforcement diameter and reinforcement corrosion rates was observed using a portion of the survey data. The results are shown in Figure 16. Considering the effects of concrete cover thickness, the results were divided into two groups with 75mm as the boundary. As shown in the figure, the survey data is widely scattered and no clear correlation could be observed between the reinforcement diameter and the reinforcement corrosion rates. Figure 17 shows the results of considering reinforcement with the same diameter as a single group and analyzing the relationship between average reinforcement corrosion rates and reinforcement diameters for every group. Even this figure does not show any clear effects of the reinforcement diameter on reinforcement corrosion rates. So with a reinforcement diameter ranging from 10 mm to 25 mm, there is no practical problem preventing the evaluation of the reinforcement corrosion speed based on the reinforcement corrosion rates multiplied by elapsed years.

(2) Concrete Cover Thickness

Figures 18 to 20 show the relationship between concrete cover thickness and reinforcement corrosion rates categorized by elapsed years. As the figure shows, despite considerable scattering, the thicker the concrete cover, the smaller the reinforcement corrosion rates. This is a result of the fact that because there is more data in the concrete cover thickness range from 50 mm to 100 mm than in the concrete cover thickness range exceeding 100 mm, it is highly likely that the survey data includes data which diverges sharply from the mean data. So concrete cover thickness was classified for each 25 mm, the reinforcement corrosion rates for each of these classes was considered to be a single group, and the relationship of the mean value with the concrete cover was organized for each elapsed year. The results are presented in Figure 21. The figure shows the number of data items whose mean values were observed. The figure also reveals a tendency for the reinforcement corrosion rates to decline as the concrete cover thickness increases. This result coincides with the results of the survey by Otsuki et. al.[4]

Figure 22 shows the relationship between standard deviation of the cross section reduction rates and concrete cover thickness by elapsed years. The standard deviation is an almost constant value, which is not influenced by the concrete cover thickness.

From the above studies, it can be concluded that concrete cover thickness influences reinforcement corrosion rates; the thicker the concrete cover, the smaller the cross section reduction rates.

(3) Elapsed Years

The relationship between elapsed years and reinforcement corrosion rates was analyzed for only two categories-reinforcement such as shear reinforcement embedded at relatively shallow locations and reinforcement such as main reinforcement embedded at relatively deep locations-defined by 75 mm as the boundary concrete cover thickness. The results are presented in Figures 23 and 24. Because both figures reveal a substantial rise in the cross section reduction rates between 21 and 23 years, it is assumed that corrosion began before 20 years had elapsed. Regardless of the large degree of scattering, data for each elapsed year was treated as a group, and the mean value and standard deviation were observed for each group. The results are shown in Figures 25 and 26 respectively. Both figures also present the numbers of data whose mean values were observed. And as both figures show, the mean value of the reinforcement corrosion rates tends to increase as the years pass, but the standard deviation is not clearly related to the elapsed years.

(4) Other Factors

Figures 27 and 28 show the relationships between member category and reinforcement corrosion rates and between compressive strength and reinforcement corrosion rates respectively. The two figures reveal substantial scattering, but no clear relationship between the reinforcement corrosion rates and either the member category nor the compressive strength. While it is assumed that these factors do effect the reinforcement corrosion rates, the relationship is supposedly hidden in the large scattering of data.

(5) Reinforcement Corrosion Speed in Tokyo Bay

The results of past studies have indicated only a small scattering of reinforcement corrosion rates and a tendency for the corrosion rates to increase with elapsed year. Here, the intersection of the regression linear equation and the elapsed years as shown in Figure 25 is considered to represent the time when corrosion begins, and its slope is assumed to be the reinforcement corrosion speed. According to this figure, the time when corrosion begins is about 10 years with a cover thickness between 25 mm and 75 mm, about 20 years for cover thicknesses between 75 mm and 150mm, and basically the thicker the concrete cover thickness, the later the corrosion begins. The reinforcement corrosion speed is about 0.31%/year for a concrete cover thickness between

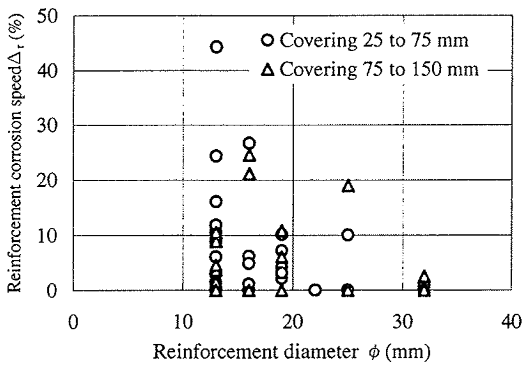

Figure 16. Relationship between reinforcement diameter and reinforcement corrosion speed.

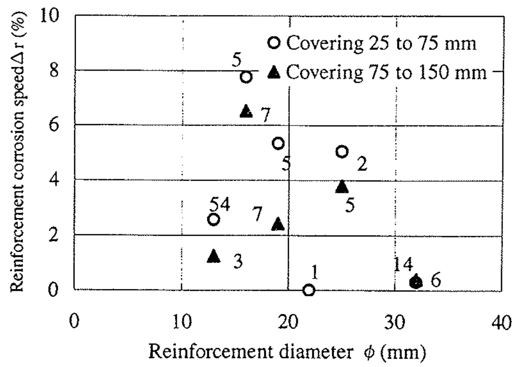

Figure 17. Relationship between reinforcement diameter and reinforcement corrosion speed.

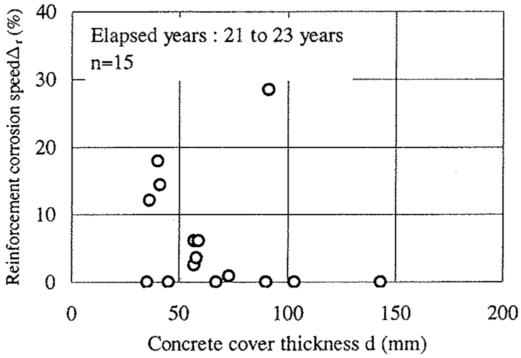

Figure 18. Relationship between concrete cover thickness and reinforcement corrosion speed.

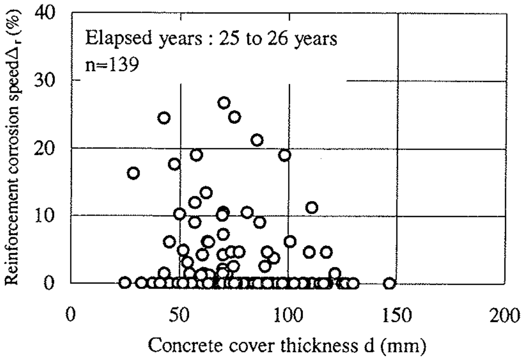

Figure 19. Relationship between concrete cover thickness and reinforcement corrosion speed.

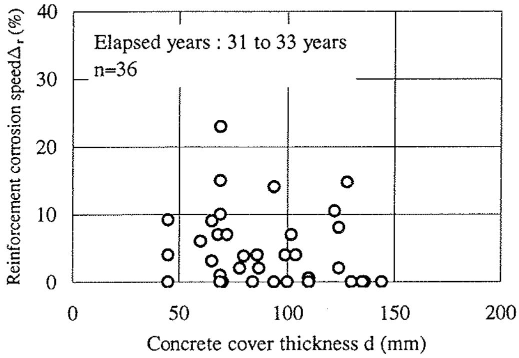

Figure 20. Relationship between concrete cover thickness and reinforcement corrosion speed

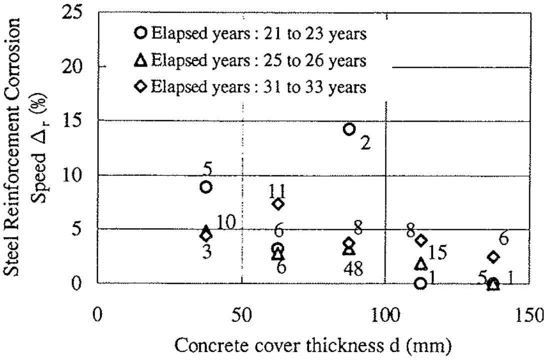

Figure 21. Relationship between concrete cover thickness and reinforcement corrosion speed (mean value).

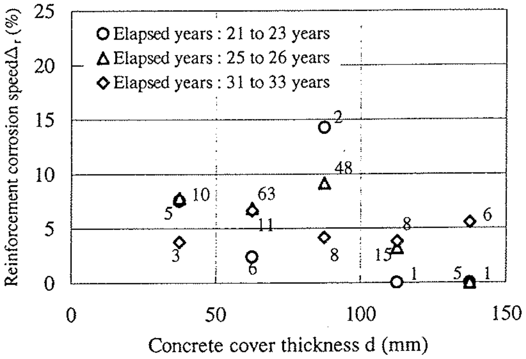

Figure 22. Relationship between concrete cover thickness and reinforcement corrosion speed (mean value).

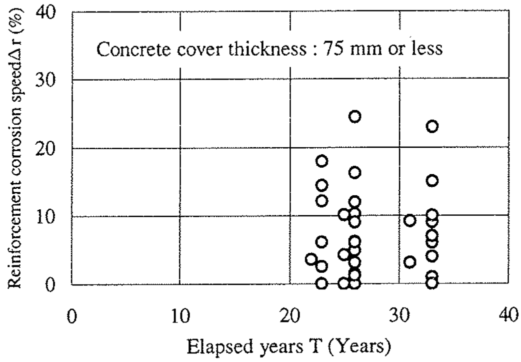

Figure 23. Relationship between elapsed years cross section reduction rate.

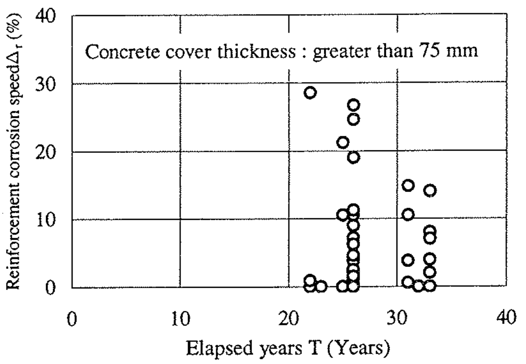

Figure 24. Relationship between elapsed years cross section reduction rate.

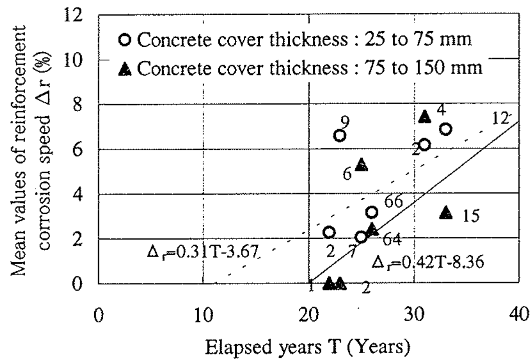

Figure 25. Relationship between elapsed years cross section reduction rate (mean value).

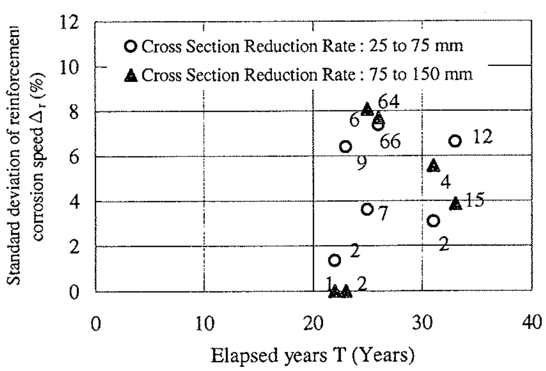

Figure 26. Relationship between elapsed years cross section reduction rate (standard deviation).

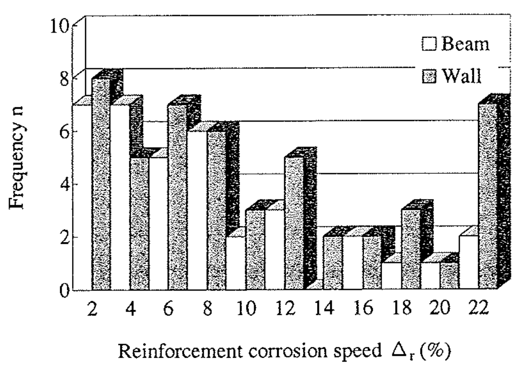

Figure 27. Relationship between member category and reinforcement corrosion rate.

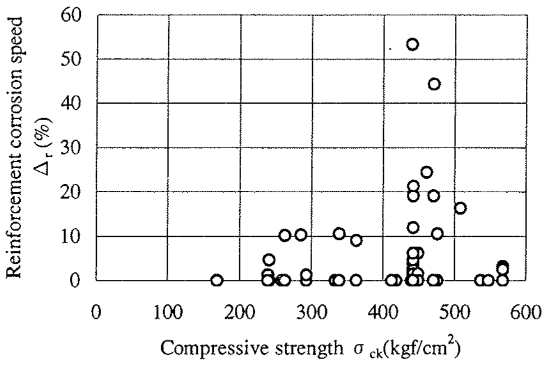

Figure 28. Relationship between compressive strength and reinforcement corrosion speed.

25 mm and 75 mm, and about 0.42% /year for thicknesses between 75 and 150 mm, but when the scattering of data is considered, the values are judged to be almost identical, and not correlated with concrete cover thicknesses. Therefore, from the data used in this study, it can be concluded that corrosion speed is about 0.35%/year, which is the mean value of the reinforcement corrosion speed in Tokyo Bay.

4.CONCLUSIONS

Based on inspection data concerning reinforced concrete structures on the seashore surrounding Tokyo Bay, factors influencing the surface chloride ion density, equivalent diffusion coefficient, and reinforcement corrosion were studied. Within the range of this study, the following data was revealed.

(1) The only factors which influence the surface chloride ion density are member location, and compressive strength; other factors were observed to have no effect on the equivalent diffusion coefficient.
(2) The surface chloride ion density in Tokyo Bay is represented by an almost normal distribution, with a mean value of 8.84 kg/m^3 and a standard deviation of 5.78 kg/m^3. And the equivalent diffusion coefficient is represented as a lognormal distribution with mean value of $1.73\times10^{-8} cm^2/sec.$ and a standard deviation of $1.59\times10^{-8} cm^2/sec.$
(3) No clear correlation was observed between the reinforcement corrosion rates and the reinforcement diameter; but, the corrosion speed was found to be higher with the thinner the concrete cover and greater number of elapsed years. The member category and compressive strength do not appear to have any effect on reinforcement corrosion rates.
(4) A relationship between elapsed years and reinforcement corrosion rates was observed; with this time when corrosion begins and reinforcement corrosion speeds were estimated. The results reveal that regardless of the high degree of scattering of the data, the thicker the concrete cover, the later the corrosion starts, and the reinforcement corrosion speed is estimated at about 0.35 %/year.

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