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Quantitative Evaluation for Resistance of Chloride Attack on Concrete Members Using Hot Dip Galvanized Rebar

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Abstract

Galvanization has been considered as one of the corrosion protection methods for steel bars in corrosive environment, but there are some concerns that zinc dissolves gradually when the galvanized steel bar is in a high alkaline environment as in concrete. Therefore, in Japan, galvanized steel bars are seldom used for concrete structures as corrosion protection methods.

However, structural design shifted from specification design to performance-based design in recent years. Therefore, even if the zinc in concrete dissolves gradually, we can predict quantitatively the period when the concrete structures maintains its durability by clarifying how much the zinc plated film decreases in thickness during an in-service period. Accordingly, the use of galvanized steel bars can be considered as an effective corrosion protection method if durability of concrete structures satisfies their designed service life.

In this study, we performed immersion tests in the water solutions which simulated concrete and exposure tests under marine environment using RC specimens to confirm the corrosion resistance of galvanized steel bars in concrete. From the results, we build the performance-based durability design method of RC structures using galvanized steel bars by measuring quantitatively of the corrosion rate of Zn plated film.

Key words: Galvanized steel bars, corrosion Resistance, Immersion Tests, Exposure Tests, Performance-Based Design Method

1. Introduction

Galvanization has been listed as one of the corrosion protection methods for steel bars in corrosive environment. Since "Guideline on design and application methods of galvanized steel reinforcement for concrete structures (draft)" [1)] was enacted in 1980 and "Recommendations for corrosion protection of offshore concrete structures (draft) -revised edition-" [2)] was enacted in 1983, the practical application as corrosion protection methods for reinforcement had been advanced. However, since zinc is amphoteric substance, dissolution of the zinc plated film was feared in a highly alkaline environment such as concrete. Therefore, galvanized steel bars were excluded from the effective corrosion protection methods.

In the current, structural design has been shifted from specification design to performance-based design. Therefore, even if the zinc in concrete dissolves gradually, we can predict quantitatively the period when the concrete structures maintains its durability by clarifying how much the zinc plated film decreases in thickness during an in-service period. Accordingly, the use of galvanized steel bars can be considered as an effective corrosion protection method if durability of concrete structures satisfies their designed service life.

In this study, we performed immersion tests in the water solutions which simulated concrete and exposure tests under marine environment using RC specimens, to confirm the corrosion resistance of galvanized steel bars in concrete, and then to build the performance-based durability design method of RC structures using galvanized steel bars by measuring quantitatively of the corrosion rate of Zn plated film.

2. Outline of Experiments

2.1 Exposure Tests Under Marine Environment

2.1.1 Specimens

The shape of specimens are shown in Figure 1. The dimension of specimens were 10 cm × 10 cm × 60 cm prisms. Mix proportion of concrete is shown in Table 1. Water-cement ratio (W/C) in concrete is 50%. The following materials were used: Ordinally Portland Cement (OPC, density: 3.16g/cm^3) as cement, river sand (density: 2.64g/cm^3) from Fujigawa as fine aggregate, and crushed stone (density: 2.56g/cm^3) from Kagoshima Prefecture as coarse aggregate. Galvanized steel bars were used D10 deformed rebars with a plating film thickness of 100μm. Cover depth of specimens is 3cm. Crack with the target width of 0.2 mm was introduced into the center of the specimens by bending loading, and both ends of the specimens were fastened with bolts so as not to block the crack. The specimens were covered with epoxy resin 12 cm on both ends.

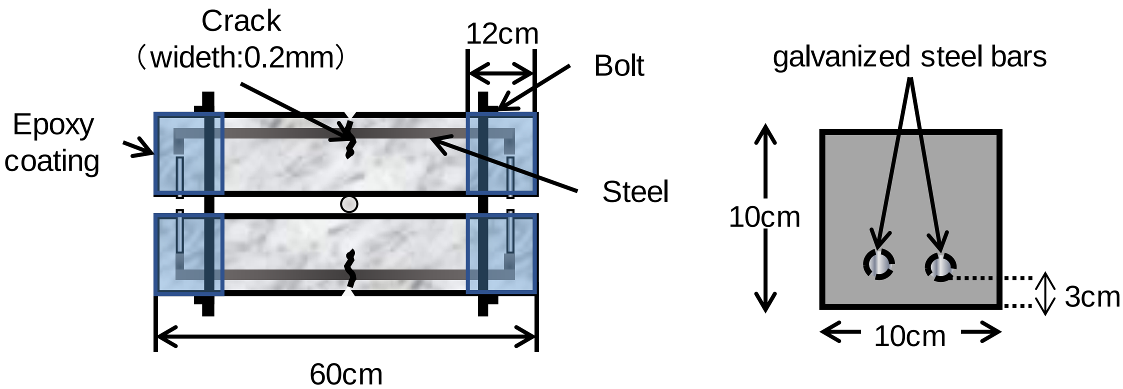

Figure1 specimens

Table1 Mix proportion of concrete

Gmax (mm)	Slump (cm)	Air (%)	W/C (%)	s/a (%)	Unit volume (kg/m^3)				Chemical Admixture (%by weight of cement)	
					W	C	S	G	AEWRA	AEA
20	8.0±2.5	4.0±1.5	50	42.5	175	350	759	1015	0.2	0.006

2.1.2 Exposure test

Figure 2 shows the installation of the specimens in exposure test site. They were installed in the tidal zone (M.S.L.) and marine atmosphere (H.W.L.+1.1m) in a marine exposure facility at Taniyama Port, Kagoshima city.

The exposure period is 3 years.

Tidal zone Marine atmosphere

Figure2 Exposure test

2.2 Immersion tests in a high alkaline aqueous solution

Figure 3 shows the specimens and the immersion test methods. Stainless steel bolts were attached to the steel bars, and the end of rebar of specimens were painted with epoxy resin. The length of the test section of rebar was 8 cm. In Case 1, D10 deformed reinforcing steel was used, and in Case 2, round rebar with φ16 was used. In Case 1, galvanized steel bars and steel bars were used, and in Case 2, only galvanized steel bars were used. The specimens were immersed in the solution as shown in Table 2 and **Table 3**. Here, saturated aqueous solution of calcium hydroxide simulates pore solution in concrete, and for comparison, distilled water and aqueous solution of sodium hydroxide adjusted to pH12.6 was used. In order to evaluate the effect of chloride ion, the solution was adjusted so that the total chloride ion amount was 0 kg/m^3 and 3.3 kg/m^3 for Case 1 and 0 ~ 16 kg/m^3 for Case 2 to simulate the total chloride ion amount in concrete using OPC with W/C=50%. In addition, in Case 2, solutions of OPC or BB mixed with much water were used to evaluate the different of saturated calcium hydroxide aqueous solution and pore solutions of concrete.

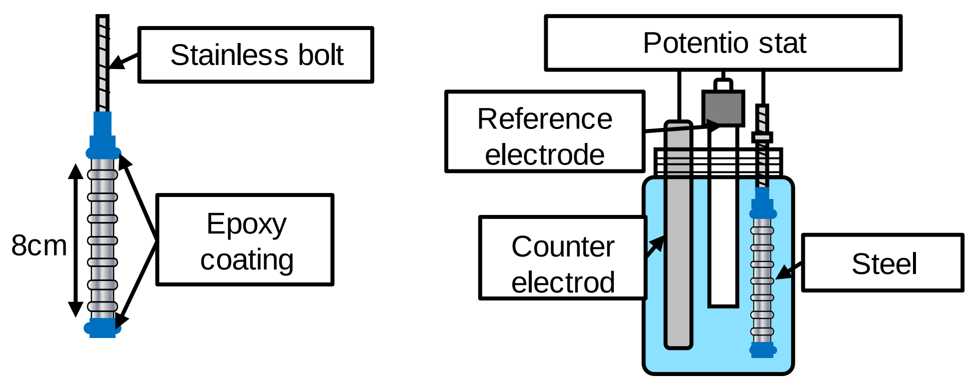

Figure 3 Specimen and immersion test method

Table 2 Immersion solutions for Case1

solutions	pH	Cl^-(kg/m^3)
H_2O	—	0
		3.3
$Ca(OH)_2$	12.6	0
		3.3
NaOH		0
		3.3

Table3 Immersion solutions for Case2

solutions	pH	Cl^-(kg/m^3)
$Ca(OH)_2$	12.6	0~16
Solution of OPC mix with mach water		
Solution of BB mix with mach water		

The flow of the linear polarization tests for measurement of corrosion rate of steel bars is shown in Figure 4. During the specimens were immersed in the test solution at constant of 20°C, the half-cell potential was monitored and the polarization curves were measured when the potential behavior was stabilized. In the linear polarization tests, the sweep speed was set to 20 mV/min, and both anode and cathode were polarized from the half-cell potential to about 300 mV in positive or negative side.

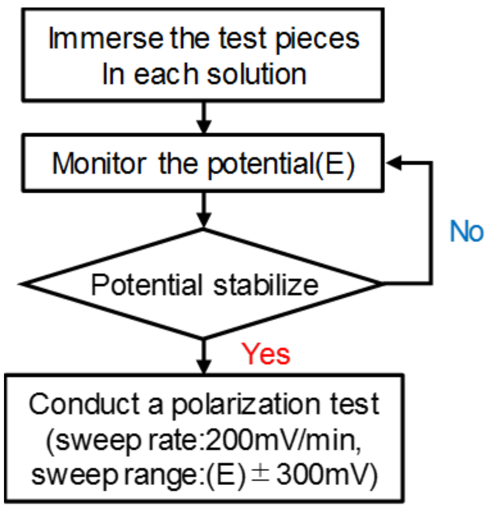

Figure4 Flowchart for polarization test

3. **Results and Discussion**

3.1 Evaluation of corrosion of galvanized steel bars by exposure tests results

Appearance of rebar as corrosion conditions of galvanized steel bars obtained from exposure tests are shown in Figure 5. Temporal change of corrosion area of galvanized steel bars at crack or sound parts in concrete specimens in exposure to tidal zone and marine atmosphere are shown in Figure 6. White rust peculiar to zinc can be seen on the galvanized steel bars. However, the degree of corrosion is different depending on the exposure environment, and when exposed to the tidal zone, corrosion occurs widely in the crack part, and the progress of corrosion tends to be intense immediately after the start of exposure. This result is expected to be affected by the relatively large crack width, but it is considered that the progress of corrosion is accelerated in the part where seawater penetration is easy. Slight corrosion was observed in the sound part of specimens exposed in tidal zone, and it was found that the corrosion was milder in comparison with the cracked part, though the corrosion progressed. On the other hand, partial corrosion can be observed in the crack part of specimens exposed in marine atmosphere, but the corrosion hardly progressed with time. In the sound part of specimens, corrosion was not observed. From these results, it was inferred that the degree of corrosion was different depending on the installation environment, and that galvanized steel bars had a very high corrosion resistance in a relatively dry environment such as the marine atmosphere.

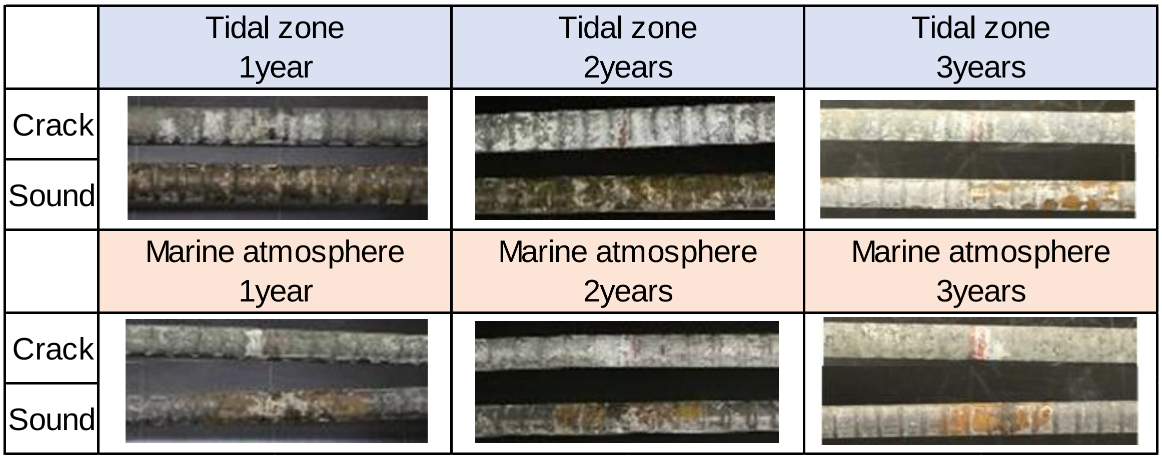

Figure5 Corrosion condition of the galvanized steel bars

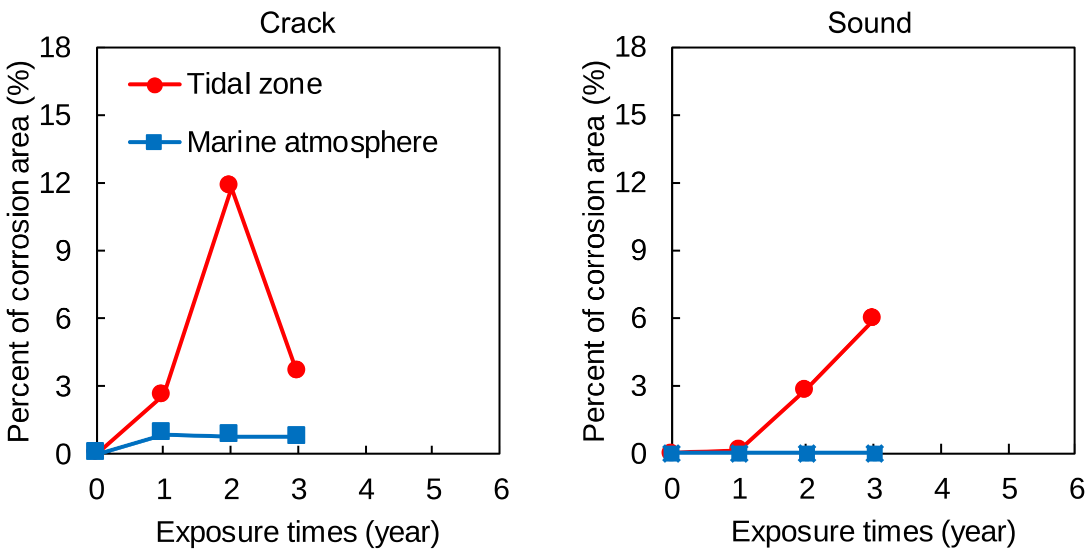

Figure6 Percent of corrosion area of the galvanized steel bars

3.2 Effect of installation environment on corrosion rate of galvanized steel bars

Figure 7 shows the relationship between corrosion rate measured by two-frequency impedance method and total chloride ion content in concrete for specimens exposed to marine atmosphere and tidal zone. From this result, it was confirmed that corrosion rate of the galvanized steel bars tended to increase with the increasing of chloride ion content in concrete at the rebar position in both environments. It was also confirmed that the corrosion rate changed by the difference of the installation environment. It is considered that this result is affected by the difference in water content in concrete. Therefore, the corrosion rate of galvanized steel bars in concrete exposed in a relatively dry environment such as marine atmosphere was estimated to be 0.7 times or less than that exposed in wet environment such as tidal zone.

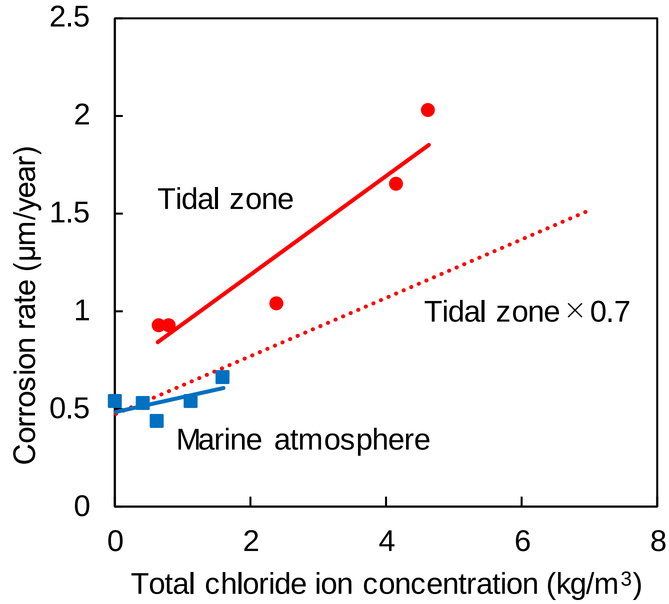

Figure7 Relationship between corrosion rate of galvanized steel bars and total chloride ion concentration in concrete

3.3 Evaluation of corrosion rate of galvanized steel bars by Immersion tests

The results of the polarization tests performed on Case 1 are shown in Figure 8. Both solutions were highly alkaline at pH12.6, but the polarization curves differed greatly between $Ca(OH)_2$ and NaOH solutions. The behavior of the polarization curve when the galvanized steel bars were immersed in NaOH solution showed corrosion behavior of cathode control type. Therefore, cathodic polarization curve drew the diffusion limit of oxygen state, corrosion rate of galvanized steel bars is determined only by the dissolved oxygen concentration regardless of the existence of chloride ion. This suggested that the zinc plated surface in NaOH solution was in a very active state. Therefore, it was considered that the corrosion rate became very high. On the other hand, the cathodic polarization curve of galvanized steel bars immersed in a saturated aqueous solution of $Ca(OH)_2$ showed concentration diffusion, which is a corrosion behavior of mixed control of anodic and cathodic polarization. It was inferred that CaHZn was formed by a chemical reaction of zinc with calcium in concrete on the zinc plated surface, and acted as diffusion

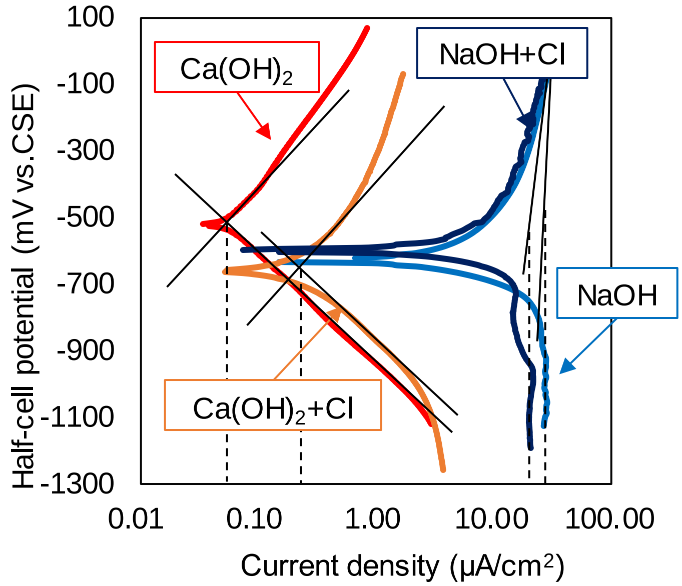

Figure 8 Polarization curves of galvanized steel bars

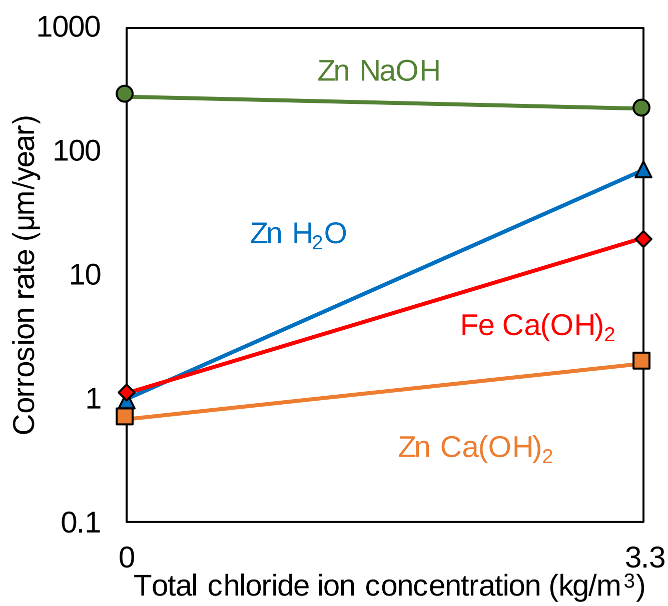

Figure 9 Relationship between corrosion rate and total chloride ion concentration (Case1)

barrier. From this fact, it can be considered that the zinc plated surface was almost in the passivation state due to the diffusion barrier by corrosion products, and the corrosion rate became very low. However, it was confirmed that the corrosion rate increased due to the existence of chloride ion in solution. Therefore, it was clarified that the protective effect was lowered by the influence of chloride ion.

Next, the relationship between the corrosion rate of galvanized steel bars and steel bars and the total chloride ion concentration in immersion solution from the immersion test in

Case 1 is shown in Figure 9. It was found that the corrosion rate of galvanized steel bars in distilled water with or without chloride ion was at the same level as that of steel in saturated $Ca(OH)_2$ solution. The corrosion rate of galvanized steel bars in saturated $Ca(OH)_2$ solution was lower than that of steel in the same solution and the corrosion rate of galvanized steel bars in NaOH solution was 100 times higher than that in the same highly alkaline environment.

The relationship between corrosion rate of galvanized steel bars and chloride ion concentration on the zinc plated surface obtained from the immersion tests and the exposure tests is shown in Figure 10. In the immersion tests, the corrosion rate was estimated from the potential-current density relationship obtained from the linear polarization tests. In the exposure tests, the corrosion rate was calculated from the polarization resistance measured by the two-frequency impedance method. In both results, the corrosion rate of the galvanized steel bars tended to increase with the increase of chloride ion concentration. However, the corrosion rate was very low, and when the chloride ion concentration was 0 kg/m^3, the corrosion rate was about 1μm/year in all the results, and it can be seen that the corrosion rate was about 2μm/year or less even in a state containing high concentration of chloride ion. In addition, from the test result obtained for the immersion tests, the galvanized steel bars immersed in saturated $Ca(OH)_2$ solution

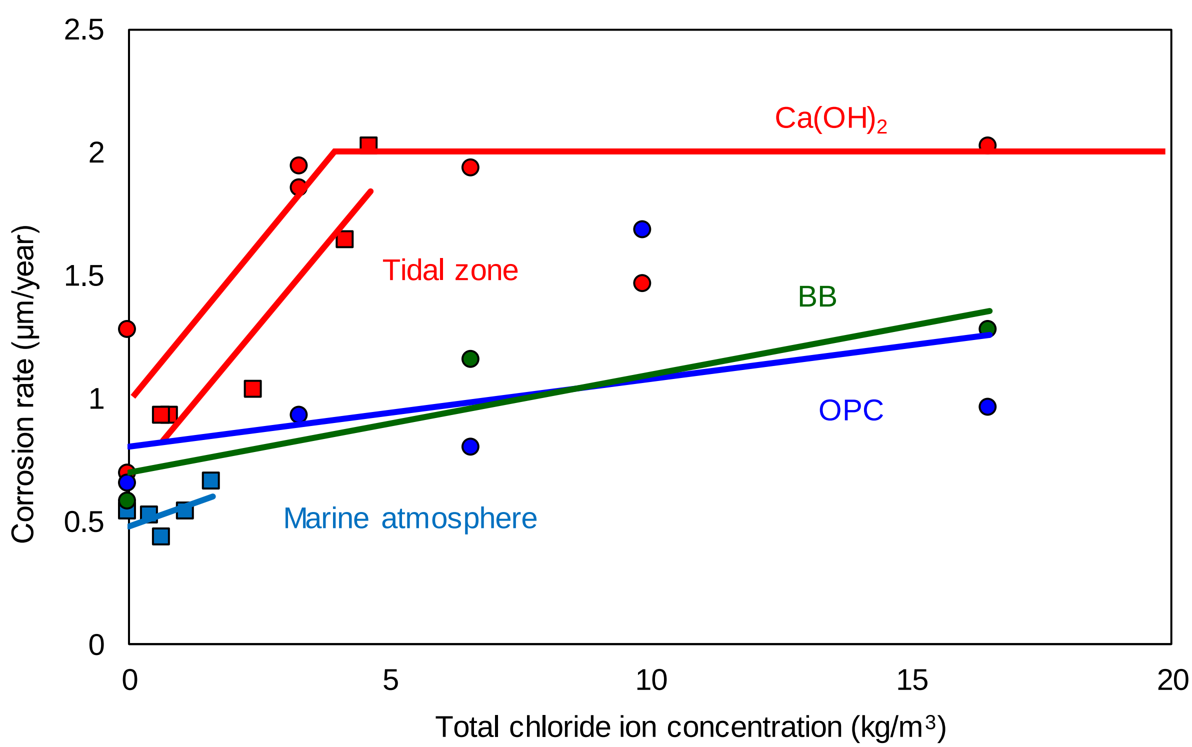

Figure 10 Relationship between corrosion rate and total chloride ion concentration

showed the highest corrosion rate. However, it was confirmed that the corrosion rate tended to peak when the chloride ion content was about 3kg/m^3. This suggests that the corrosion of galvanized steel bars in saturated $Ca(OH)_2$ solution was controlled by oxygen diffusion, and that the diffusion limit of oxygen was reached at the corrosion rate of about 2μm/year. And, the corrosion rate obtained from the result of immersion in the solution of cement mixed with much water and the result of the exposure test tended to be lower than the result of immersion in the saturated $Ca(OH)_2$ solution. This may be due to the presence of cement hydrates or hydration products on the surface of the galvanized steel bars, which act as a barrier to diffusion of oxygen.

4. Proposal of performance-based durability design method for galvanized steel bars

_On the basis of the above test results, the performance-based durability design method on corrosion of the galvanized steel bars was examined. First, the definition of the consumed thickness of zinc plating is shown in Figure 11. The limit value of the consumed thickness of zinc plating set to the minimum thickness of the zinc plated film of galvanized steel bars used for RC structures. The design value of the consumed thickness of zinc plating can be set to the film thickness at which zinc plated is consumed by corrosion during the design service life. Therefore, when the design value of the consumed thickness of the zinc plating is smaller than the limit value of the consumable thickness, base steel of galvanized steel bars do not corroded because it is protected by zinc plating during the design service life. In performance-based design, it will be checked whether the performance on the corrosion is satisfied by this method.

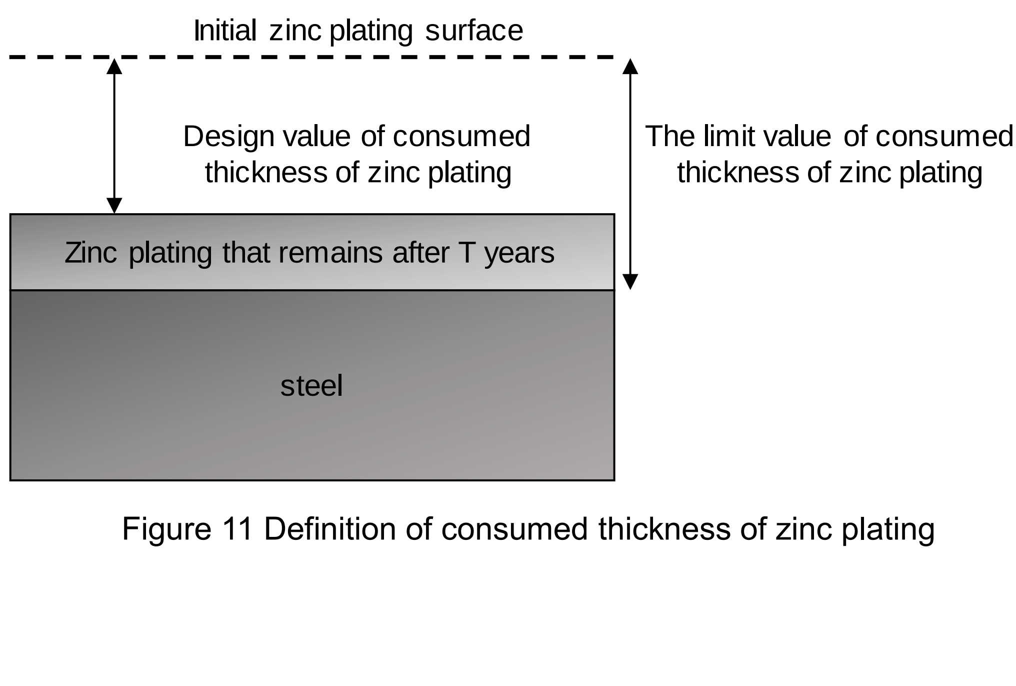

Figure 11 Definition of consumed thickness of zinc plating

From the experimental results, the consumed rate (corrosion rate) of zinc plating in concrete is decided by various factors such as the quality of concrete, the installed environment, and the chloride ion concentration and so on. Therefore, the consumed film thickness during the design service life (*T* years) is considered to be shown a function as shown in Equation 1.

$$W = \int_0^T f(pH, RH, Cl \cdots)\, dt \tag{1}$$

Where *W* is the consumed thickness of zinc plating after *T* years (μm), *pH*: pH of concrete, *RH*: moisture content of concrete, *Cl*: chloride ion concentration, and *T* is the design service life. However, it is difficult to formulate Equation 1 from previous research results. Therefore, we tried to convert from function to coefficients refer to the experimental results as shown in Equation 2.

$$W_d = \int_0^T k_m \cdot g(Cl)\, dt \tag{2}$$

Where W_d is the design value of the consumed thickness of zinc plating after *T* years, k_m is the coefficient expressing the effect of the moisture content around the galvanized steel bars on the consumed rate of zinc plating, *g (Cl)* is the function expressing the consumed rate of zinc plating with the penetration of chloride ion, and *T* is the design service life. Here, *g*(*Cl*) is expressed Equation 3 or Equation 4 depending on the test results of Figure 10.

$$g(Cl) = 0.3 \cdot Cl + 1.0 \quad (0.0\text{kg/m}^3 < Cl \leqq 3.3\text{kg/m}^3) \tag{3}$$

$$g(Cl) = 2.0 \quad (3.3\text{kg/m}^3 < Cl) \tag{4}$$

Where *Cl* is the total chloride ion content (kg/m^3) at the rebar position.

Regarding k_m, as the consumed rate of zinc plating is affected by the moisture around galvanized steel bars, it was decided to classify according to the installed environment. In this study, marine environment was divided into the splash zone, tidal zone and under-seawater as the wet environment and the marine atmosphere as the dry environment. Environmental correction values obtained from the results of the marine exposure test

(Figure 7) were used as shown in Table 4.

Table 4 k_m vale

Environmental condition	Wet condition ex) Taidal zone	Dry condition ex) Marine atmoshere
k_m	1	0.7

A case study was conducted using Equation 2. The calculation condition shows Table 5. Relation of Design service life and cover depth is shown in Figure 12. From this result, It can be seen that the design service life is extended when using galvanized rebar as compared to ordinary steel bars. When a galvanized steel bars with a thickness of 100μm was used, the design service life was predicted to be 50 years or more in a wet environment and 75 years or more in a dry environment.

From the above, it was confirmed that galvanized steel bars had higher chloride induced deterioration resistance than steel even in severe chloride induced deterioration environment, and that they had sufficient corrosion protection effect.

Table 5 calculation condition for case study

cement	Ordinally Portland cement
W/C	0.5
Cover depth	5 ~ 10 cm
installed environment	Wet condition, Dry condition
Surface chloride ion concentration	13.0 kg/m^3
Initial film thickness of zinc plating	0, 75, 100 μm
Limit film thickness of zinc plating	0 μm (start of corrosion of base steel)
C_{lim} of steel bars	2.0 kg/m^3

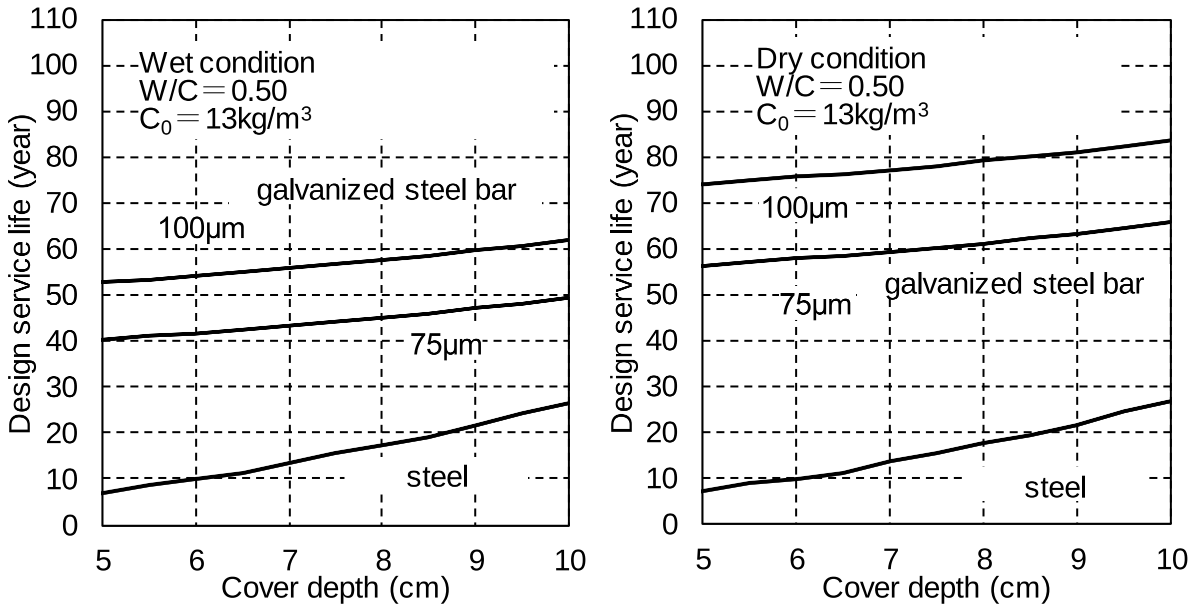

Figure 12 Relation of Design service life and cover depth

5. Conclusions

Conclusions obtained from our research are shown as follows:

1) It was confirmed that the degree of corrosion was different depending on the installation environment, but that galvanized steel bars in concrete had a high corrosion resistance even in a severe environment such as the marine environment.
2) Corrosion rate of galvanized steel bars in concrete is very low, because CaHZn was formed by a chemical reaction of zinc with calcium in concrete on the zinc plated surface, and act as protective film like a passive film.
3) Corrosion rate of galvanized steel bars in concrete exposed in wet environment such as tidal zone was 1~2 (μm/year). On the other hand, the corrosion rate of galvanized steel bars in concrete exposed in a relatively dry environment such as marine atmosphere was estimated to be 0.7 times or less than that exposed in wet environment such as tidal zone.
4) From the experimental results, we build the performance-based durability design method of RC structures using galvanized steel bars. when a galvanized steel bars with a thickness of 100μm was used, the design service life was predicted to be 50 years or more in tidal zone and 75 years or more in marine atmosphere in the conditions shown in table 5.

ACKNOWLEDGEMENTS

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