Service Life Estimation of Concrete Structures Reinforced with Cr-bearing Rebars under Macrocell Corrosion Conditions Induced by Cracking in Cover Concrete

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Cracked concrete members reinforced with Cr-bearing rebars were assumed for the purpose of developing Cr-bearing rebars having the required corrosion resistance in macrocell corrosion environments induced by cracking in cover concrete. The service life of concrete structures reinforced with Cr-bearing rebars was then estimated based on a macrocell corrosion rate model, and their Cr content to achieve a service life of 100 years was calculated. As a result, the service life of concrete reinforced with Cr-bearing rebars was found to increase as their Cr content increased regardless of the corrosive environment type. The calculation also revealed that Cr contents of 16% or more and 13% or more would lead to a service life of over 100 years in harsh and moderate chloride attack zones, respectively. In a carbonation zone, the Cr content to achieve a service life of over 100 years was calculated to be 9% or more.

KEY WORDS: Cr-bearing rebar; service life estimation; macrocell corrosion; crack.

1. Introduction

Service life estimation procedure of a reinforced concrete structure consists of defining the limit state of a subject structure regarding each of its deterioration mechanisms and carrying out precise estimation of the service life of the structure to the limit states. This technique is effective in examining the durability of reinforced concrete structures. Precise estimation of the service lives of new and existing reinforced concrete structures has become highly significant from the aspect of bringing about a long service life of reinforced concrete structures, as the importance of durability design and maintenance of reinforced concrete structures have now become widely recognized. The service life of a reinforced concrete structure can be estimated by estimating the changes of the corrosion rate over time in various corrosive environments, thereby estimating the time to the limit states of the structure. The forms of reinforcing steel corrosion in concrete are roughly classified into two types, microcell corrosion and macrocell corrosion, depending on the surface conditions of concrete, the environment, and the nonuniformity of materials. A major cause of macrocell corrosion, which is induced by material nonuniformity, is nonuniform penetration of corrosion factors through the cracks in cover concrete. The penetration rates of corrosion factors, such as carbon dioxide, chloride ions, oxygen, and water, through cracks in concrete surfaces are higher than through sound concrete surfaces,1,2) causing macroscopic nonuniformity in concrete covering reinforcing steel, thereby causing macrocell corrosion. The rate of macrocell corrosion is higher than that of microcell corrosion, leading to the serviceability limit state of structures in a short time. Investigation into macrocell corrosion is therefore vital for evaluating the durability of reinforced concrete structures.3–5)

For this reason, a large number of studies have been conducted for the purpose of inhibiting rebar corrosion, these have been mostly concentrated on the improvement of concrete quality to improve corrosion resistance,6–8) while little attention has been paid to corrosion-inhibiting rebar. However, research and development of corrosion-resistant rebar with low life-cycle cost are now anticipated in view of the increasing repair cost for reinforced concrete structures.9–12)

With this as a background, the authors have been investigating the corrosion resistance of Cr-bearing rebars having lower alloying elements, such as chromium, nickel, and molybdenum, than general stainless steel to allow production by processes similar to those of normal steel.13–15)

In this study, the service life of concrete structures reinforced with Cr-bearing rebars was investigated in macrocell corrosion environments induced by cover concrete cracking as part of a study for the development of Cr-bearing rebars having corrosion resistance suitable for the corrosive environments to which reinforced concrete structures are to be constructed. Based on the estimated service life, the Cr content of Cr-bearing rebars to achieve a corrosion resistance for up to 100 years was also calculated.
2. Study Overview

A concrete member reinforced with a Cr-bearing rebar having a single crack was assumed. The penetration rates of Cl\(^-\) and CO\(_2\) through the cracked and sound areas were determined to express the material nonuniformity between the cracked and sound areas in terms of the difference in the chloride concentration and carbonation/uncarbonation. Also, the rates of macrocell and microcell corrosion were calculated based on the equations for calculating the polarizability and half-cell potential of Cr-bearing rebars, as well as an equation for calculating the concrete resistance, using the corrosion factors as parameters. The amounts of macrocell and microcell corrosion calculated from these corrosion rates were added, and the time required for the sum to reach the threshold amount of rust causing a crack in cover concrete was calculated as the service life. The use of the sum of macrocell and microcell corrosion amounts is intended to incorporate the possibility of their coexistence in rebar under cracked cover concrete. The amount of rust that would cause cracking in cover concrete was adopted as the limit state of reinforced concrete structures. The macrocell corrosion rate was determined using a model consisting of electrical circuits in concrete. Also, the polarization resistance of anodic bars in various corrosive environments was determined and substituted into the Stern–Geary equation and Faraday’s law to calculate the corrosive environments was determined and substituted into the Stern–Geary equation and Faraday’s law to calculate the polarization resistance and half-cell potential of Cr-bearing rebars in a corrosive environment.

3. Formulation of Diffusion/Penetration Rates of Corrosion Factors

Macrocell corrosion induced by cracking in cover concrete is caused by material nonuniformity resulting from the differences in the penetration rates of Cl\(^-\) and CO\(_2\). For this reason, it is necessary first to determine the penetration rates of Cl\(^-\) and CO\(_2\) separately in cracked and sound areas in order to estimate the service life of a structure reinforced with Cr-bearing rebars in a corrosive environment.

3.1. Diffusion/Penetration Rate of CO\(_2\)

Though a number of studies have been conducted on the carbonation of concrete to evaluate its durability,\(^{16,17}\) they have been disproportionately concentrated on the penetration of CO\(_2\) in sound concrete, while few have dealt with the carbonation of defective concrete having cracking. The penetration rate of CO\(_2\) in sound concrete can generally be expressed as a square root of time as given in Eq. (1). The carbonation depth, \(C\), can be determined by setting an appropriate coefficient, \(A\), which is the coefficient of carbonation rate determined by the materials and mixture proportions of concrete and corrosion conditions. In this study, coefficient \(A\) was determined based on Eq. (2), which was proposed by the Architectural Institute of Japan.\(^{18}\) Table 1 gives the determination coefficients for \(A\) calculated based on the concrete materials, concrete mixture proportions, and corrosion conditions to be adopted for the service life estimation in this study.

The penetration rate of CO\(_2\) through a crack is known to be significantly higher than through a sound area, even when the crack width is small.\(^{19–21}\) The CO\(_2\) penetration rate was therefore regarded as infinite in this study. In other words, concrete in the cracked area was regarded as being carbonated from the beginning of service life calculation. This is because the crack width of 0.4 mm adopted in this study, for which no repair is required by the guidelines for repair of concrete structures, is judged as being large enough for CO\(_2\) to pass through.\(^{22}\)

\[
C = A\sqrt{t} \quad \ldots \ldots \ldots (1)
\]

\[
A = 1.41 \cdot \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot \beta_1 \cdot \beta_2 \cdot \beta_3 \quad \ldots \ldots \ldots (2)
\]

where \(C\) is carbonation depth (cm), \(A\) is determination coefficient for carbonation rate, \(t\) = time (year), \(\alpha_1\) is coefficient for concrete type (aggregate type), \(\alpha_2\) is coefficient for cement type, \(\alpha_3\) is coefficient for proportioning (water–cement ratio), \(\beta_1\) is coefficient for air temperature, \(\beta_2\) is coefficient for moisture, \(\beta_3\) is coefficient for CO\(_2\) concentration.

3.2. Penetration Rate of Cl\(^-\)

Penetration of chloride ions in concrete is a phenomenon resulting from complicated combinations of the transfer of chlorides associated with water seepage through voids and diffusion in a pore solution, as well as chemical fixing and adsorption of chlorides. Fick’s second law (Eq. (3)) is generally used as a basic equation to express the diffusion of chloride ions in sound concrete.

\[
\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} \quad \ldots \ldots \ldots (3)
\]

where \(C\) is chloride ion concentration of concrete (kg/m\(^3\)), \(t\) is exposure time (s), \(x\) is distance from concrete surface (cm), \(D_x\) is diffusion coefficient (cm\(^2\)/s).

By solving the equation under the initial condition of \(C(x,0)=0\) and the environmental condition of \(C(0,t)=C_0\) (constant), Eq. (4) is obtained.

\[
C(x,t) = C_0 \left[1 - \text{erf} \left(\frac{x}{2\sqrt{D_x t}}\right)\right] \quad \ldots \ldots \ldots (4)
\]

where \(C(x,t)\) is chloride ion concentration at time \(t\) and distance \(x\) (kg/m\(^3\)), \(C_0\) is apparent surface chloride ion concentration (kg/m\(^3\)), \(\text{erf}\) is error function, \(x\) is distance from surface (cm), \(D_x\) is diffusion coefficient (cm\(^2\)/s), \(t\) is elapsed time (s).

| Table 1. Parameters of determination coefficient for carbonation rate. |
|--------------------|-------------------|
| \(A\)              | Determination coefficient for carbonation rate |
| \(\kappa\)          | 1.71 Fixed number |
| \(\alpha_1\)       | 1.0 Normal concrete |
| \(\alpha_2\)       | 1.0 Normal Portland cement |
| \(\alpha_3\)       | 0.22 Coefficient for proportioning (water-cement ratio) |
| \(\beta_1\)        | 1.0 Coefficient for air temperature (Tokyo=15.9°C) |
| \(\beta_2\)        | 1.0 Coefficient for moisture (Tokyo=65%) |
| \(\beta_3\)        | 1.0 Coefficient for CO\(_2\) concentration (Outdoor=0.05%) |
The chloride ion concentration at a specific time and position can be calculated by determining the surface chloride ion concentration and the chloride ion diffusion coefficient through concrete and substituting into Eq. (4). In this study, the surface chloride ion concentration was determined according to the distance from the coast based on Eq. (5) while assuming that it is constant. Also, the diffusion coefficient of chloride ions in concrete structures was determined based on Eq. (6), which comprises the terms for the cement type and water–cement ratio. In this study, the penetration rate of Cl\(^{-}\) in sound concrete was determined based on Eqs. (4) to (6).

The penetration rate of Cl\(^{-}\) in the cracked area was determined by using 200 cm\(^2\)/year, the value proposed as the diffusion coefficient of Cl\(^{-}\) in cracked areas by the Japan Society of Civil Engineers.\(^{19}\) Figure 1 shows the penetration phenomenon of Cl\(^{-}\) and CO\(_2\) through a cracked area of concrete. The values in the figure denote the diffusion coefficient of Cl\(^{-}\) and rate determination coefficient for CO\(_2\) in cracked and sound areas.

\[ C_0 = 0.53 - 0.08 \ln x \]  
where \( C_0 \) is NaCl % (per mass of concrete), \( x \) is distance from the coast (m).

\[ \log D_x = -3.9(W/C)^2 + 7.2(W/C) - 2.5 \]  
where \( W/C \) is water–cement (binder) ratio, \( D_x \) is diffusion coefficient of Cl\(^{-}\) (cm\(^2\)/year).

### 4. Macrocell Corrosion Rate Model

#### 4.1. Modeling of Electrical Circuits

In order to calculate the macrocell corrosion current through rebars in the cracked area, the electrical circuits in the concrete including the cracked area should first be modeled. Figure 2 shows the electrical circuit of macrocell corrosion formed in reinforced concrete having a single crack.\(^{23,24}\) The electrical circuit consists of the half-cell potential, polarization resistance, and concrete resistance in each segment. In this circuit, the half-cell potential, polarization resistance, and concrete resistance values excepting potentials \( V_2, V_4, V_6, V_8, \) and \( V_{10} \) are those determined by non-destructive testing. Simultaneous equations, Eqs. (7) to (11), are obtained by substituting these values into the circuits and applying the rule that, according to the continuity condition, “the sum of the currents flowing from adjacent points is zero” to the points of unknown potentials, 2), 4), 6), 8), and 10).

\[
\frac{V_1 - V_2}{R_{12}} + \frac{V_2 - V_4}{R_{24}} = 0 \quad \ldots (7)
\]
\[
\frac{V_2 - V_4}{R_{24}} + \frac{V_3 - V_4}{R_{34}} + \frac{V_6 - V_4}{R_{64}} = 0 \quad \ldots (8)
\]
\[
\frac{V_4 - V_6}{R_{56}} + \frac{V_5 - V_6}{R_{56}} + \frac{V_8 - V_6}{R_{108}} = 0 \quad \ldots (9)
\]
\[
\frac{V_6 - V_8}{R_{68}} + \frac{V_7 - V_8}{R_{78}} + \frac{V_{10} - V_8}{R_{108}} = 0 \quad \ldots (10)
\]
\[
\frac{V_5 - V_{10}}{R_{510}} + \frac{V_6 - V_{10}}{R_{610}} = 0 \quad \ldots (11)
\]

By solving these simultaneous equations, the unknown potentials at points 2), 4), 6), 8), and 10), that is \( V_2, V_4, V_6, V_8, \) and \( V_{10} \), respectively, are determined, thereby determining the potential at all points. The current between points 1) and 2), between 3) and 4), between 5) and 6), between 7) and 8), and between 9) and 10) calculated based on Ohm’s law are the macrocell corrosion currents that flow across the surfaces of rebar. One of these values, \( I_{56} \) that flows between points 5) and 6) is the macrocell corrosion current for the cracked area. A macrocell corrosion current is converted to a corrosion rate based on Faraday’s second law. Equations (12) and (13) express Ohm’s law and Faraday’s second law, respectively.

\[
I_{56} = \frac{V_5 - V_6}{R_{56}} \quad \ldots (12)
\]
\[
V_{\text{macro}} = \frac{M}{nF} \times I_{56} \quad \ldots (13)
\]

where \( V_{\text{macro}} \) is rate of macrocell corrosion (g/cm\(^2\)/s), \( M \) is atomic weight of Fe (≈ 55.8), \( n \) is valence number (≈ 2), \( F \) is Faraday number (≈ 96 500, C/mol), \( I_{56} \) is macrocell corrosion current for the cracked area (A/cm\(^2\)).

Also, the microcell corrosion rate of rebar in the cracked area can be determined by substituting the polarization resistance in the cracked area, \( R_{56} \), into the Stern–Geary equation and Faraday’s second law. Equation (14) gives the microcell corrosion rate of the anodic rebar in the cracked area.

\[
V_{\text{micro}} = \frac{M}{nF} \times \frac{K}{R_{56}} \quad \ldots (14)
\]
where $V_{\text{micro}}$ is rate of microcell corrosion (g/cm²/s), $M$ is atomic weight of Fe ($=55.8$), $n$ is valence number ($=2$), $F$ is Faraday number ($=96,500$, C/mol), $R_{56}$ is polarization resistance for the cracked area ($\Omega \cdot \text{cm}²$).

Accordingly, the macrocell and microcell corrosion rates can be determined based on Eqs. (7) to (11), if the half-cell potentials and polarization resistances for cracked and sound areas of rebar and the concrete resistances of the electrical circuit formed in each segment are known. Each parameter to be input in simultaneous Eqs. (7) to (11) is variable depending on the temperature, chloride ion concentration, and pH value at the rebar level. It is therefore necessary first to accurately determine each parameter in respective corrosive environments for calculating the corrosion current for each type of corrosive environment.

In this study, the polarization resistance and half-cell potential of Cr-bearing rebars, which vary under corrosive conditions, were determined using the equations for calculating them in each corrosive environment derived in the authors' past studies. The macrocell and microcell corrosion rates that change over time were then calculated by solving Eqs. (7) to (14) using these parameters.

### 4.2. Formulation of Polarization Resistance and Half-cell Potential

The authors have formulated in their previous study the polarization resistance and half-cell potential of Cr-bearing rebars in mortars simulating environments involving chloride attack, carbonation, and combined deterioration (chloride attack plus carbonation). This was based on the measurement of their polarization resistance and half-cell potential and multiple regression analysis of the data using the Cr content, chloride ion concentration, and carbonation as variables. Equations (15) and (16) give the regression equations of the polarization resistance and half-cell potential, respectively, of Cr-bearing rebars. Figures 3 and 4 show the relationships between the regression values and test values of polarization resistance and half-cell potential, respectively. These figures reveal strong correlation between analyzed and measured values. It is therefore inferred that the polarization resistance and half-cell potential of Cr-bearing rebars in concrete under various corrosive conditions involving chloride attack, carbonation, and combined deterioration can be estimated by using these regression equations.

For this reason, it was decided in this study to determine the polarization resistance and half-cell potential of Cr-bearing rebars in corrosive environments using Eqs. (15) and (16). The scope of this equation ranges from 0 to 16% in terms of the Cr content. A Cr content of 0% refers to SD345. Chloride ion concentration ranges of pH values of 12.5 and 8.5 refer to 0 to 24 kg/m³ and 0 to 12 kg/m³, respectively. Note that the pH values of carbonated and uncarbonated concrete were assumed to be 8.5 and 12.5, respectively. In other words, the changes in the chloride ion concentration for the pH value of 12.5 refer to deterioration induced by chloride attack, whereas their changes for the pH value of 8.5 refer to combined deterioration caused by both chloride attack and carbonation. Also, pH values of 12.5 and 8.5 with zero chloride represent sound and carbonated environments, respectively.

\[
\ln(R_p) = 0.268Cr - 3.423 \ln(1+Cl^-) - 0.033T + 0.111pH + 0.179pH \cdot \ln(1+Cl^-) + 4.634 \quad \text{...... (15)}
\]

\[
R = 0.95, \quad S = 0.56
\]

\[
E = 0.021Cr + 0.182ln(1+Cl^-) + 0.088pH - 0.03pH \cdot \ln(1+Cl^-) - 1.357 \quad (V \text{ vs. } \text{CSE}) \quad \text{...... (16)}
\]

\[
R = 0.94, \quad S = 0.05
\]

where $R_p$ is polarization resistance (kΩ·cm²), $E$ is half-cell potential ($V$ vs. CSE), $Cr$ is Cr content of Cr-bearing rebars (%), $Cl^-$ is chloride ion concentration at rebar level (kg/m³), $T$ is temperature at rebar level (°C), $pH$ is pH value at rebar level (= 12.5 (uncarbonated) and 8.5 (carbonated)).

### 4.3. Formulation of Concrete Resistance between Rebar Segments

In order to define the macrocell corrosion rate of rebar segments based on the macrocell electrical circuit model, it is necessary to determine the concrete resistance between rebar segments. For the calculation of concrete resistance...
between rebar segments, it is also necessary to limit the shape of concrete. Figure 5 shows the cross-section of a specimen. If a beam with a cross-section measuring 10 cm by 10 cm is regarded as the range of the flow of macrocell corrosion current generated per rebar, then the concrete resistance per unit length in the longitudinal direction can be determined by Eq. (17). The concrete resistance between rebar segments was determined by multiplying the concrete resistance per unit length by the distance between rebar segments, 10 cm. Equation (18) is the equation for calculating the concrete resistance between rebar segments. In order to determine the concrete resistance between rebar segments using Eqs. (17) and (18), however, the specific resistance of concrete should be defined. Generally known values of 10 and 15 kΩ cm were therefore assumed to be the specific concrete resistances for environments under chloride attack and carbonation, respectively.

\[
R_{\text{unit}} = \rho (10 - \pi r^2) \text{ (Ω/cm)} \quad \ldots \quad (17)
\]

\[
R_{\text{ab}} = 10 \cdot R_{\text{unit}} \text{ (Ω)} \quad \ldots \quad (18)
\]

where \( R_{\text{unit}} \) is concrete resistance per unit length (Ω/cm), \( R_{\text{ab}} \) is concrete resistance between rebar segments (Ω), \( \rho \) = specific resistance of concrete (Ω cm), \( r \) = radius of rebars (0.95 cm).

4.4. Amount of Rust for Crack Onset

The limit state of reinforced concrete structures is mostly defined as the onset of longitudinal cracking. This is currently deemed rational, as longitudinal cracking accelerates the subsequent corrosion rate, is easy to judge from the aspect of maintenance, and demands repair from the aspect of aesthetics.

A number of studies have therefore been conducted on the amount of rust to cause cracking on the concrete surface.27-29 Among these studies, Morinaga30-32 has proposed a threshold corrosion loss for a given rebar diameter and cover depth as given in Eq. (19). This is an equation frequently adopted for the calculation of the amount of rust causing cracking in cover concrete. This equation allows determination of the rust amount that causes cracking in cover concrete given the rebar diameter and cover depth. In this study, the amount of rust on Cr-bearing rebars causing cracking in cover concrete was defined using Eq. (19). By regarding this amount as the limit state of reinforced concrete structures, the authors conducted a service life estimation. Table 2 gives the amount of rust for crack onset for each corrosive environment.

\[
Q_{cr} = 0.602 \left( 1 + 2c/d \right)^{0.85}d \quad \ldots \quad (19)
\]

where \( Q_{cr} \) is amount of rust (Fe₂O₃) on rebar causing cracking in cover concrete (10⁻⁴ g/cm²), \( c \) is concrete cover thickness (mm), \( d \) is rebar diameter (mm).

5. Service Life Estimation of Concrete Structures Reinforced with Cr-bearing Rebars

5.1. Outline of Corrosive Environments and Subjects of Analysis

The corrosive environment conditions to which concrete structures reinforced with Cr-bearing rebars are to be subjected and the structures to be analyzed are outlined in this section. The corrosive environments were roughly classified into three types: environments involving harsh chloride attack, moderate chloride attack, and carbonation. The environments involving harsh and moderate chloride attack were regarded as places located at distances of 50 m and 250 m from the coast, respectively.33 The environment involving carbonation was assumed to be located at a distance of 1 km or more where rebar corrosion due to the attachment/penetration of air-borne chloride ions was not likely to occur.33 As for the climatic conditions, the seasonal mean temperatures and annual mean humidity in Okinawa and Tokyo were adopted for each of the harsh and moderate chloride attack zones and carbonation zone. The water-cement ratio of the subject reinforced concrete structures was 60%. The concrete cover thicknesses were 20, 40, and 60 mm in harsh and moderate chloride attack zones and 20 and 30 mm in the carbonation zone. Table 2 gives the analysis conditions for the corrosive environments and sub-

| Distance from the coast | 50m (Harsh chloride attack) | 250m (Moderate chloride attack) | 1km or more (Carbonation) |
|------------------------|-----------------------------|-------------------------------|---------------------------|
| Temperature (°C)       | Spring(25), Summer(30), Autumn(22), Winter(17) | Spring(25), Summer(30), Autumn(22), Winter(17) | Spring(15), Summer(25), Autumn(17), Winter(7) |
| Humidity (%)           | 80                           | 80                            | 70                        |
| Water-cement ratio (%) | 60                           | 60                            | 60                        |
| Diffusion coefficient of CF (m²/year) | Crack area | No crack area | Crack area | No crack area | Crack area | No crack area |
|                        | 20000 | 261 | 20000 | 261 | 0 | 0 |
| Determination coefficient for carbonation rate CO₂ (A) | Crack area | No crack area | Crack area | No crack area | Crack area | No crack area |
|                        | 0 | 0.362 | 0 | 0.362 | 0 | 0.378 |
| Surface chloride ion content (kg/m³) | Crack area | No crack area | Crack area | No crack area | Crack area | No crack area |
|                        | 3.46 | 1.44 | 0 | 0 |
| Rebar diameter (mm)    | 19                           | 19                            | 19                        |
| Concrete cover thickness (mm) | 20 | 40 | 60 | 20 | 40 | 60 |
| Amount of rust for crack onset (mg/cm²) | Crack area | No crack area | Crack area | No crack area | Crack area | No crack area |
|                        | 3 | 4.7 | 6.2 | 3 | 4.7 | 6.2 | 3 | 3.8 |
5.2. Calculation Conditions for Penetration Processes of Cl⁻ and CO₂

This section presents the calculation conditions for the penetration processes of Cl⁻ and CO₂ to determine their penetration rates through cracked and sound areas. Table 2 gives the coefficients necessary for calculating their penetration rates.

1. The diffusion coefficient of Cl⁻ in the cracked area is assumed to be 20 000 mm²/year.
2. The diffusion coefficient of CO₂ in the cracked area is assumed to be infinite, with the cracked area being assumed to have been carbonated from the beginning of service life calculation.
3. All chloride ions are assumed to be penetrating from outside, with no intrinsic Cl⁻ in concrete materials being considered. The diffusion coefficient of Cl⁻ is assumed to be constant throughout the analysis.
4. The chloride ion concentration at the surface of concrete is assumed to be constant throughout the analysis.
5. The chloride ions penetrating from outside are assumed not to react with other substances within concrete.
6. The surface concentration and diffusion coefficient of CO₂ are assumed to be constant throughout the analysis.

5.3. Calculation Conditions for Corrosion Process of Steel

For calculating the macrocell and microcell corrosion currents through rebar in the cracked area, the calculation conditions for the steel corrosion process were defined as follows:

1. Cl⁻ and CO₂ are assumed to be readily conducted through the porous interfaces between concrete and steel and penetrate into sound cover concrete. In other words, corrosion in the cracked area is not regarded as localized corrosion of the area adjacent to cracking but assumed to be corroded in which the entire rebar segment designated to the cracked area serves as the anode of macrocell corrosion. The macrocell corrosion current is calculated on this assumption.
2. The penetration of Cl⁻ and CO₂ is assumed to occur not only from the cracked area but also from the surfaces of sound concrete with no cracking.
3. The half-cell potential and polarization resistance of anodic and cathodic zones of rebars are assumed to vary depending on the amount of chloride ions penetrating through the cracked and sound areas and whether or not the concrete is carbonated.
4. Steel with a corrosion current density of not more than 0.2 μA/cm² is judged as being passivated. In other words, when the corrosion current density is not more than 0.2 μA/cm², the amount of rust calculated based on Faraday’s law is regarded as zero.

5.4. Analysis Results and Discussion

5.4.1. Cumulative Amount of Rust

Figure 6 shows the cumulative amount of rust on Cr-bearing rebars in corrosive environments under different cover depths. This figure reveals that the cumulative amount of rust on Cr-bearing rebars increases over time regardless of the environment type. This tendency becomes less evident as the Cr content increases. In the graphs of the harsh and moderate chloride attack zones ((1) and (2)), the top parts represent the cumulative amount of rust on the anodic zone of rebar, whereas the bottom parts show the time-related changes in the concentration of chloride ions at the bar level in the cracked and uncracked areas. In the cracked area, a large amount of chloride ions is accumulated begin-
ning at an early stage, whereas the rates of chloride ion penetration and accumulation are lower in the sound area. The arrow in the bottom parts of the graphs refer to the time after carbonation reaches the rebar in the uncracked area. The time required for carbonation to reach the cover depth of 20 mm in the harsh and moderate chloride attack zones (1) and (2)) was 30.75 years. In the graph for the carbonation zone in Fig. 6, the top part refers to the cumulative amount of rust on the anodic area of rebar, and the bottom part refers to the carbonation rate in the uncracked area. Figure 6 reveals that the rate of increase in the cumulative amount of rust (corrosion rate) tends to decrease at the point when carbonation reaches the cathodic area of rebar in the uncracked area regardless of the environment type. This can be attributed to the reductions in the material nonuniformity (difference in the pH values) between the anodic rebar in the cracked area and cathodic rebar in the uncracked area due to carbonation of concrete in the uncracked area to the rebar level.

5.4.2. Service Life of Concrete Structures Reinforced with Cr-bearing Rebars

Figure 7 shows the service lives of concrete structures reinforced with Cr-bearing rebars in the three types of corrosive environments. This figure reveals that the service life increases as the Cr content increases regardless of the environment type. However, increases in the cover depth produce little life-extending effect. This can be attributed to the extremely high diffusion coefficients of Cl⁻ and CO₂ assumed in this study, which surpassed the effect of inhibiting corrosion factors by cover depth in the cracked area. This figure reveals that a corrosion resistant service life of over 100 years was calculated for Cr-bearing rebars with a Cr content of 16% or more with a cover depth of 20 mm in the harsh chloride attack zone. In the moderate chloride attack zone, the calculated service life was over 100 years when their Cr content was 13% or more with a cover depth of not less than 20 mm. In regard to the carbonation zone, a calculated service life of over 100 years was achieved by a Cr content of 9% or more with a cover depth of not less than 20 mm. Table 3 gives the Cr content of Cr-bearing rebars that achieves the calculated service life of over 100 years.

6. Conclusions

The authors estimated the service life of concrete structures reinforced with Cr-bearing rebars under macrocell corrosion conditions induced by cracking in cover concrete as part of a study for the development of Cr-bearing rebars having corrosion resistance suitable for the corrosive environment in which the concrete structure is to be constructed. Their Cr content required for achieving a service life of over 100 years was also calculated. The findings include the following:

(1) The calculated service life of concrete structures reinforced with Cr-bearing rebars increases as their Cr content increases under all corrosive environment conditions.

(2) Cr-bearing rebars with Cr contents of not less than 16% and not less than 13% are expected to achieve a service life of over 100 years in harsh and moderate chloride attack zones, respectively, with a cover depth of not less than 20 mm.

(3) In a carbonation zone, Cr-bearing rebars with a Cr content of not less than 9% are expected to achieve a service life of over 100 years with a cover depth of not less than 20 mm.

Table 3. Cr content of Cr-bearing rebars that achieves the calculated service life of over 100 years.

| Concrete cover thickness (mm) | SD345 | 3Cr | 5Cr | 7Cr | 9Cr | 11Cr | 13Cr | 16Cr |
|-----------------------------|-------|-----|-----|-----|-----|------|------|------|
| Harsh chloride attack [50m] |      |     |     |     |     |      |      |      |
| 20                          | 0.25  | 0.25| 0.5 | 0.50| 0.75| 1.00 | 2.25 | 100% |
| 40                          | 0.25  | 0.25| 0.5 | 0.50| 0.75| 1.50 | 3.25 | 10.7% |
| Moderate chloride attack [250m] |      |     |     |     |     |      |      |      |
| 20                          | 0.25  | 0.25| 0.5 | 0.75| 1.00| 2.25 | 5.75 | 100% |
| 40                          | 0.25  | 0.50| 0.75| 1.25| 1.50| 3.25 | 9.00 | 100% |
| Carbonation [1km U/E] |      |     |     |     |     |      |      |      |
| 20                          | 0.50  | 0.75| 1.00| 3.50| 3.50| 100% | 100% | 100% |
| 30                          | 0.50  | 0.75| 1.25| 3.50| 3.50| 100% | 100% | 100% |
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