STUDY ON CORROSION MONITORING OF REINFORCING STEEL BARS IN 36-YEAR-OLD ACTUAL CONCRETE STRUCTURES

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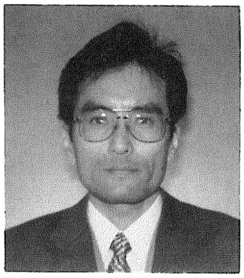

Masaru YOKOTA

To evaluate the on-site corrosion rate of steel reinforcement in actual concrete structures, a new portable corrosion rate meter based using an AC impedance technique has been developed. Corrosion diagnosis using this new instrument is carried out on 36-year-old actual concrete structures canstihuring an open channel in a coastal district. Concrete walls from the tidal zone to the splash zone were tested for half-cell potential, corrosion rate (polarization resistance), concrete cover, chloride penetration into concrete, and other factors. The corrosion penetration depth in reinforcing steel bars is estimated from the product of corrosion rate and corrosion period, which could be determined by the diffusion rate of chloride ions. Penetration depth values estimated from the corrosion monitoring results correlate well with those measured from gravimetric weight loss. On the other hand, no correlation was found between penetration depth and half-cell potential in the concrete. These resulls demonstrate that the newly developed corrosion monitoring system can successfully measure the on-site corrosion rate of steel bars in concrete structures.

Keywords : *RC structures, corrosion monitoring, polarization resistance, corrosion rate, ac impedance, chloride ions*

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1. INTRODUCTION

Recently, the deterioration of reinforced concrete structures resulting from the corrosion of reinforcing steel bars due to penetration by chloride ions has become a serious problem. In order to estimate the service life of concrete structures and to select an appropriate repair interval that will prolong service life, the development of a field corrosion monitoring technique is of great practical interest. In this work, a corrosion monitoring method using AC impedance has been investigated for the evaluation of on-site corrosion rate of steel bars and estimation of the service life of concrete structures.

In this paper, the new corrosion rate meter is described and the results of its application to actual concrete structures in a coast district are presented.

2. CORROSION RATE METER

On-site corrosion rate measurements were carried out using a new portable corrosion rate meter (see Fig.1) developed by Shikoku Research Institute Inc.. This device has the following features:

- Operates on an AC impedance principle. It has a reinforcing bar connection, a reference electrode, and an auxiliary electrode. A small sinusoidal voltage is applied, and the amplitude of the sinusoidal current response and the phase difference between the two signals are measured.
- To allow rapid measurement, the apparent polarization resistance, Rct', obtained from the AC impedance measurements at two frequencies is used, as shown in Fig.2 [1]. A high frequency of 10-1 Hz and a low frequency of 10 mHz are used.
- To define the area of reinforcing steel being polarized during measurement, the double counter electrode method is used [2], as shown in Fig.3.
- The true polarization resistance, Rct, is determined from eq.(1):

$$Rct = Rct' \times A \qquad (1)$$

$$A = \pi d \times 4 / 2 = 2 \pi d \qquad (2)$$

where A is the steel area being measured, and is equal to the surface area of the top 4cm of the reinforcing steel and d is the diameter of the steel.

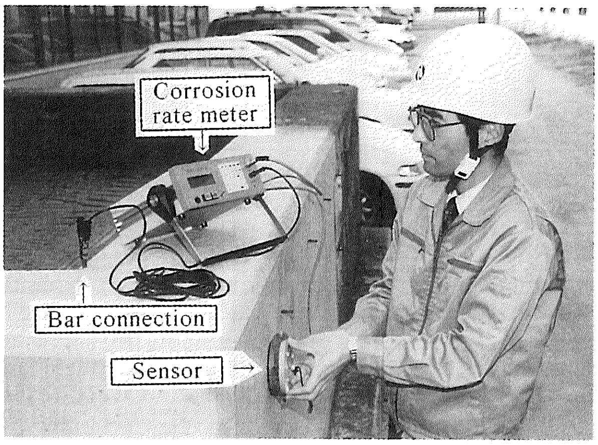

Fig.1 New portable corrosion monitoring system

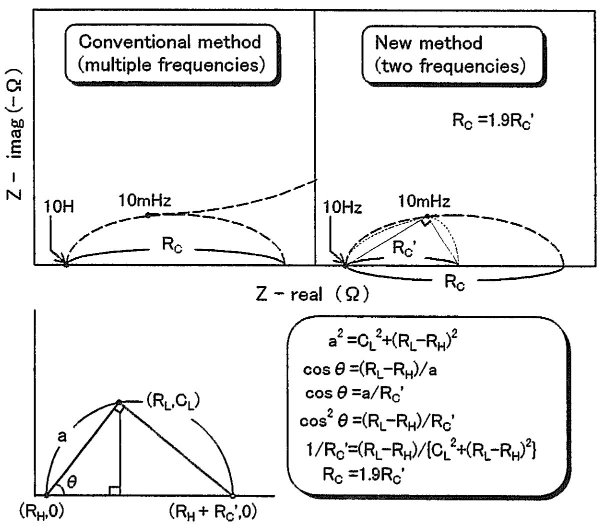

Fig.2 Newly developed method of estimating polarization resistance from AC impedance measurements

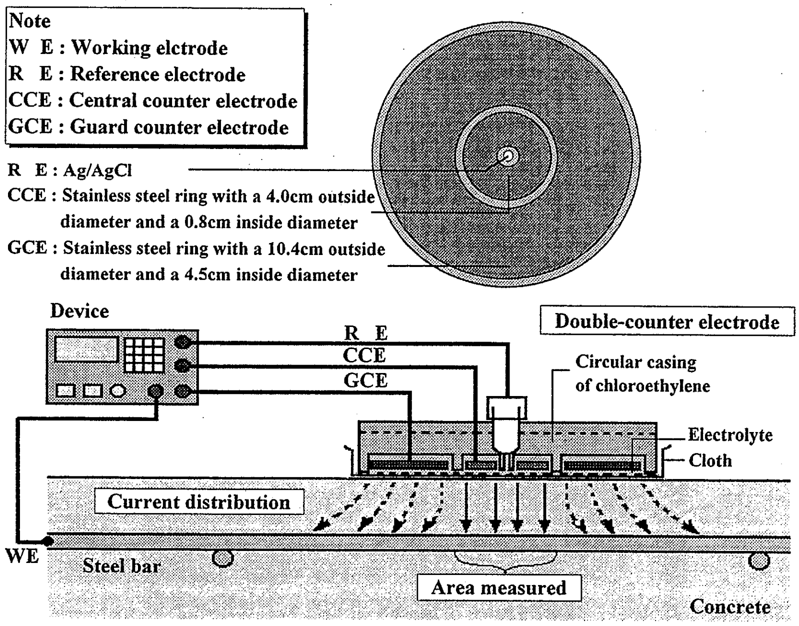

Fig.3 Principle of AC impedance measurement using a double-counter electrode

● The corrosion current density (the corrosion rate), Icorr, is estimated by the Stern and Geary equation (3).:

$$\mathrm{Icorr} = \mathrm{B} \times (1 / \mathrm{Rct}) \qquad (3)$$

where B is a constant (=0.026V). According to Faraday's law, the corrosion current density, Icorr, can be converted into a penetration rate from eq.(4). In the following text, the corrosion rate is expressed as the penetration rate (mm/year).

$$\text{Penetration rate} = 11.6 \times 10^3 \times \mathrm{Icorr} \qquad (4)$$

3. OUTLINE OF EXPERIMENT

Corrosion measurements were carried out on the steel bars in 36-year-old actual concrete structures - the concrete walls of an open channel, as shown in Fig.4, located in a coastal district on the Seto Inland Sea at Matsuyama, Ehime Prefecture. Two separate areas were chosen for corrosion monitoring. Area 1 and Area 2 were 80m and 100m from the shore, respectively. There was no evidence of surface cracking. Vertical reinforcement consisting of 19 mm diameter round bars and horizontal reinforcement consisting of 13 mm diameter round bars are arranged at intervals of 30cm and 25~30cm, respectively. The total test surface of

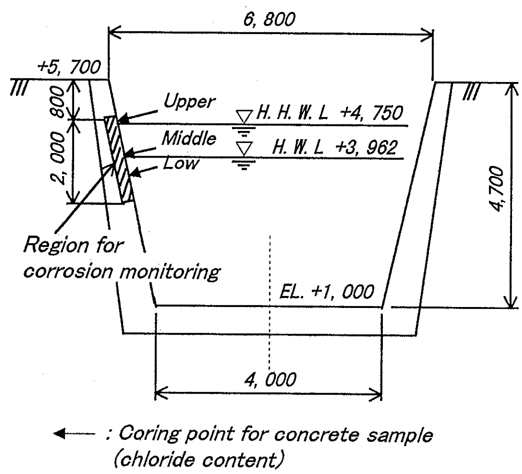

Fig.4 Cross section of tested concrete walls of an open channel

Area 1 and Area 2 was approximately 1m^2.

Concrete walls from the tidal zone to splash zone were tested for (a) half-cell potential and corrosion rate (polarization resistance) estimated from AC impedance measurements using the new portable corrosion diagnosis system, (b) chloride concentration in the concrete, (c) thickness of concrete cover, (d) quantity of corrosion and mean penetration depth from the gravimetric weight loss of steel.

4. RESULTS AND DISCUSSION

Figure 5 shows the potential, the corrosion rate estimated from polarization resistance, and the thickness of cover measured in Area 1 and 2.

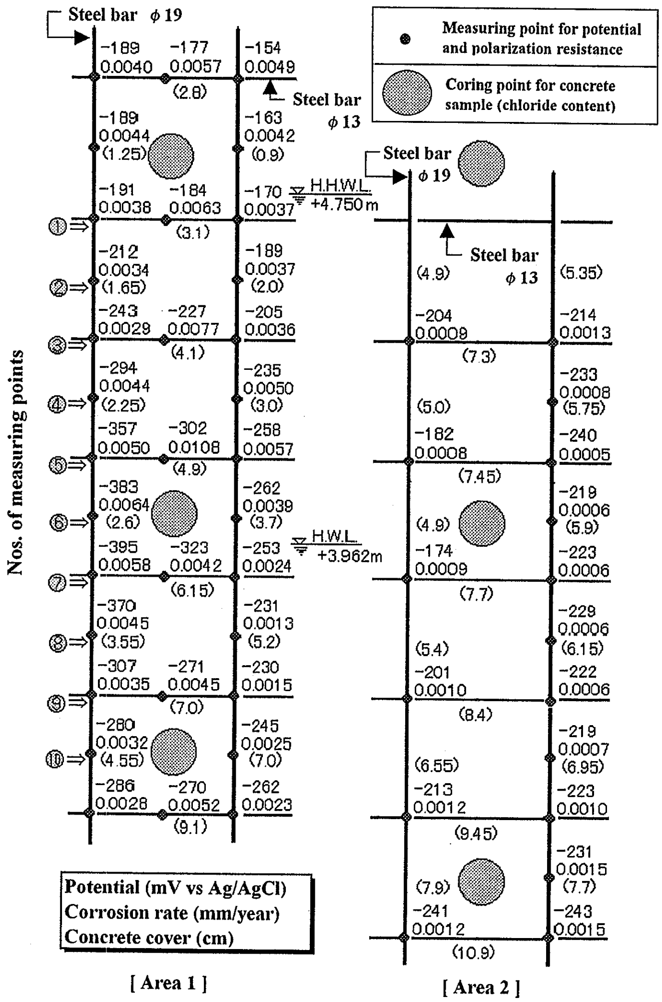

Fig.5 Half-cell potential, corrosion rate, and concrete cover measured in Areas 1 and 2

4.1 Amount of corrosion (mean penetration depth)

Figure 6 shows the distribution of mean penetration depth measured from the gravimetric weight loss of samples from two vertical reinforcing steel bars removed from part of Area 1. Corrosion was found over the whole of the steel bars except below H.W.L.-0.15m on the right bar. The mean penetration depth in the left bar reached a peak of 0.11mm at the height of H.W.L.+0.15m. The peak in the right bar was 0.026mm at the height of H.W.L.+0.3m. On the other hand, no corrosion was found on the steel bars in Area 2.

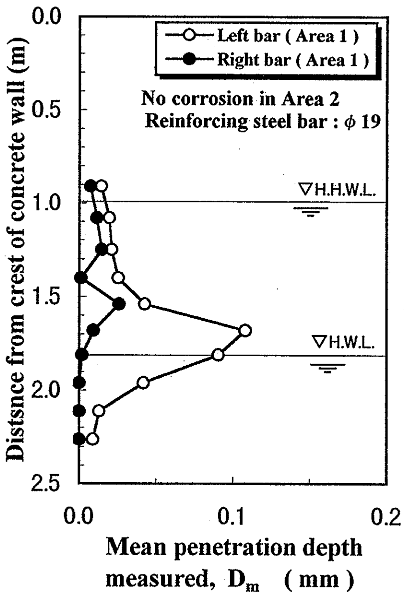

Fig.6 Vertical distribution of measured mean penetration depth of a reinforcing steel bar

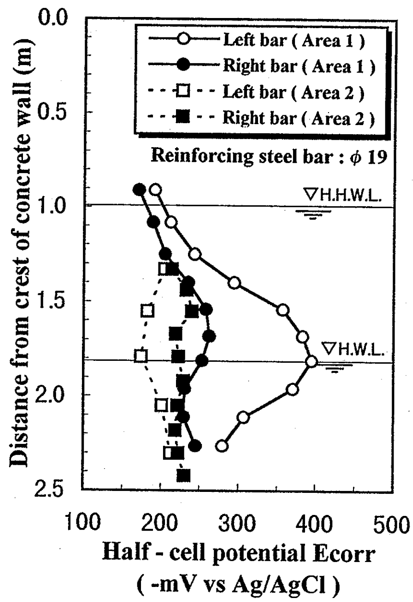

Fig.7 Vertical distribution of half-cell potential along a reinforcing steel bar

4.2 Half-cell potential

Figure 7 shows the vertical distribution of half-cell potential along a steel bar. The potential distribution for Area 1 indicated sections with a high corrosion risk. The potential value tended to fall with increasing penetration depth, as shown in Fig.6. In particular, the potentials obtained from the left bar were more negative than the ones from the right bar, becoming a minimum value (-400mV vs Ag/AgCl) at H.W.L. However, the potential distributions for Area 2 did not show the same tendency. Figure 8 shows the relationship between half-cell potential and measured mean penetration depth for the reinforcing steel.

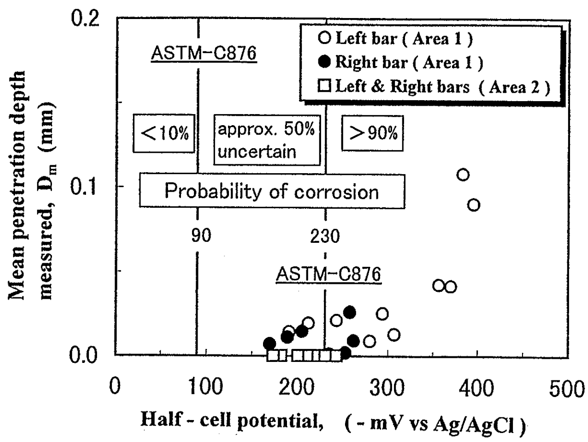

Fig.8 Relationship between half-cell potential and measured mean penetration depth of a reinforcing steel bar

4.3 Corrosion rate estimated from AC impedance measurements (polarization resistance)

Figure 9 shows the vertical distribution of corrosion rate estimated from AC impedance measurements along a steel bar. Figure 10 shows the relationship between estimated corrosion rate and measured mean penetration depth for the reinforcing steel. The corrosion rates for Area 1 and Area 2 ranged from 0.0013 to 0.0108 mm/year and from 0.0005 to 0.0015 mm/year, respectively. It appears that corrosion rates for Area 1 tend to be much higher than those for Area 2. The corrosion rates for non-corroded parts in Area 1 and 2 did not exceed 0.0015mm/year. From these results, it is indicated that the corrosion rate is superior to the half-cell potential as an index of steel corrosion.

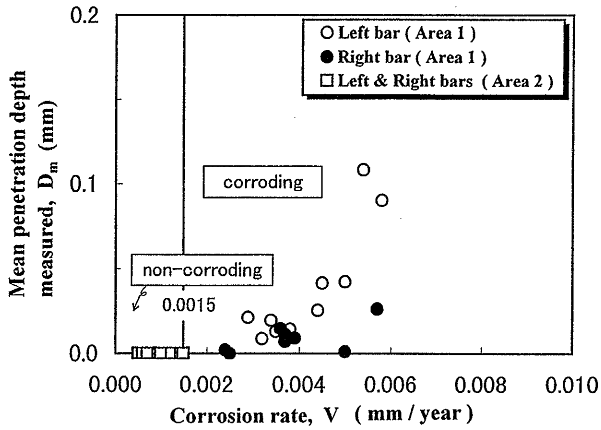

Fig.10 Relationship between estimated corrosion rate and measured mean penetration depth of a reinforcing steel bar

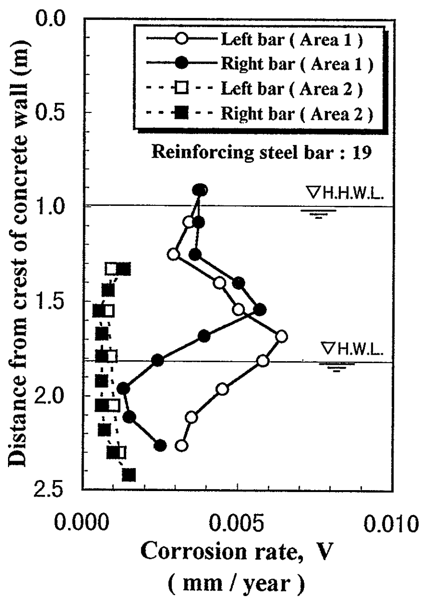

Fig.9 Vertical distributions of corrosion rate estimated by AC impedance method along a reinforcing steel bar

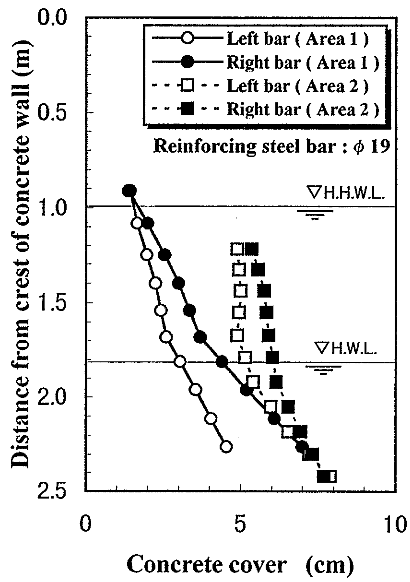

Fig.11 Vertical distribution of concrete cover along a reinforcing steel bar

4.4 Thickness of concrete cover

The vertical distribution of concrete cover thickness along a steel bar is shown in Fig.11. With increasing distance from the crest of the wall, the cover over the left and right bars in Area 1 increases from 1.5 to 5.0cm and from 1.5 to 7.0cm, respectively. On the other hand the cover depth values for Area 2, ranging from 5 to 8cm, were larger than the ones for Area 1.

4.5 Chloride content in concrete walls

The distribution of total chloride content in concrete walls from the tidal zone to the splash zone (see Fig.4), for Area 1 and 2 is shown in Fig.12, which illustrates the results for core samples from upper, middle, and lower parts of the wall. Chloride contents were measured by a potential difference titration method using a chloride - selective electrode, and are expressed in terms of Cl^- content (%) by weight of concrete. Both Area 1 and 2 show same penetration of chlorides from the external environment. Comparing the chloride content of the upper, middle, and lower parts of the walls, it is apparent that the chloride penetration increases toward the bottom of the wall, due to the influence of seawater. In the middle, at H.W.L., the chloride content of the concrete at the depth of 7.0cm from concrete surface for Area 1 and of 4.5cm for Area 2 respectively exceeds 0.1%, which is a critical value of chloride content for the generation of corrosion by chloride. Comparing the chloride content and cover, it is seen that the chloride content around the reinforcing steel in Area 1 exceeds 0.1% and, on the other hand, in Area 2 it remains less than 0.1%. These results agree with the observed corrosion, as shown in Fig.6.

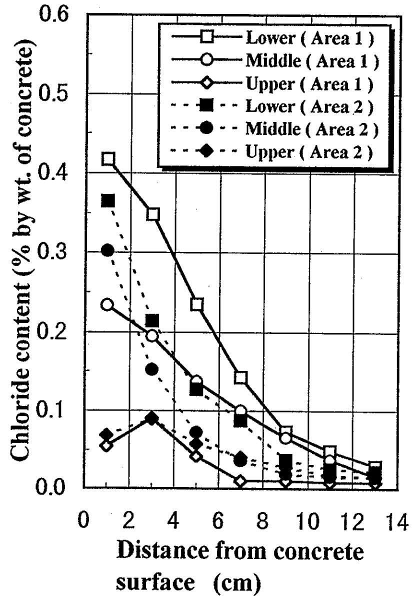

Fig.12 Distribution of chloride content in concrete walls from tidal zone to splash zone

4.6 Possibility of corrosion monitoring

The penetration depth of reinforcing steel bars was estimated from the product of the corrosion rate, v, and the corrosion period, t_c, for Area 1.

$$\text{Dest.} = v \times t_c \qquad (5)$$

where v is the corrosion rate obtained from AC impedance measurements using the new instrument and t_c is the corrosion period.

The usual deterioration process of concrete structures through steel reinforcement corrosion is as illustrated in Fig.13. Therefore, the corrosion period, t_c, is expressed by eq. (6).

$$t_c = t_m - t_i \qquad (6)$$

where t_m is the present age (36 years) and t_i is the incubation period, which is the time between construction and the beginning of corrosion by chlorides. This t_i can be calculated by the diffusion calculation given below.

The penetration of chlorides into concrete is considered a diffusion phenomenon and, according to Fick's diffusion theory, the diffusion of chloride ions is expressed by eq.(7).

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2}\right) \qquad (7)$$

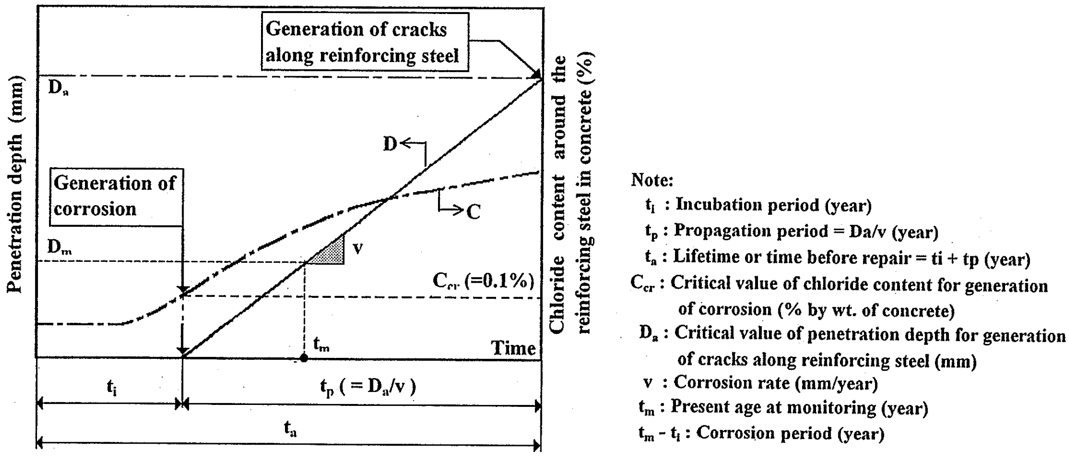

Fig.13 Deterioration process of concrete structures by the chloride-injured corrosion of steel reinforcement

Assuming that the rate of chloride penetration from the external environment into the concrete is constant, the solution of eq.(7) is indicated in eq.(8).

$$C_{x,t} = C' + W \cdot \left[2\sqrt{\frac{t}{\pi D}} \cdot \exp\left(-\frac{x^2}{4Dt} \right) - \left(\frac{x}{D} \right) \cdot \left\{ 1 - \mathrm{erf}\left(\frac{x}{2\sqrt{Dt}} \right) \right\} \right] \tag{8}$$

where $C_{x,t}$ is the chloride (Cl^-) concentration at distance x from the surface at time t, C' is the initial chloride concentration within the concrete, W is the amount of chloride penetration from the external environment into the concrete, erf is the error function, and D is the apparent coefficient of diffusion of chloride ions in concrete.

First, using the method of least squares and eq.(8), the values of C', W, and D at the measurement points were obtained by approximate calculations using the measurements of chloride content in the concrete wall, as shown in Fig.12. Consequently, C', D, and W were found to be 0.008%, $1.6 \sim 2.9 \times 10^{-8}$ cm^2/s, and $0.43 \sim 2.4 \times 10^{-9}$ %/cm$^2 \cdot$s($0.44 \sim 2.4$ g/m^2/month in NaCl), respectively.

Second, assuming that the reinforcing steel bars become active at a chloride level of 0.1% by weight of concrete, the incubation period, t_i, at each of the measurement points was calculated from these values of C', D, and W and eq.(8). And the corrosion period was obtained by subtracting the incubation period from the present age, as shown in eq.(6). Figure 14 shows the calculated vertical distribution of corrosion period. It was confirmed that initial corrosion began at H.W.L. ±0 to H.W.L.+0.15m.

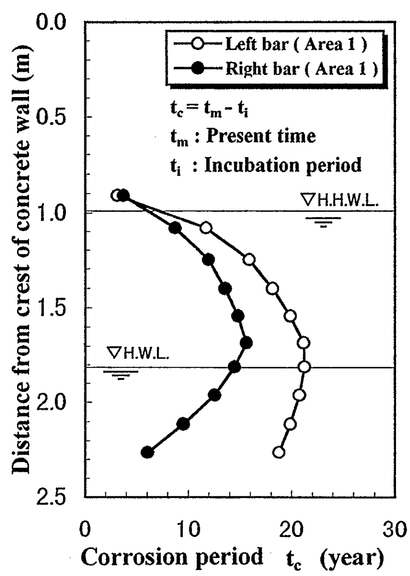

Fig.14 Vertical distribution of corrosion period along a reinforcing steel bar

Last, assuming that the corrosion rate was constant during the corrosion period, the penetration depth values obtained by corrosion monitoring were estimated from the product of v (see Fig.9) and t_c (see Fig.14). These results are shown by line graphs in Fig.15 and Fig.16. The penetration depth values measured from gravimetric weight loss are illustrated by the bar graphs, which are the same as the data in Fig.6. This proves that the penetration depth values estimated from corrosion monitoring results correlate well with those measured obtained gravimetric weight loss. Thus the newly developed corrosion rate meter is able to successfully monitor the corrosion of reinfoicing bars in actual structures.

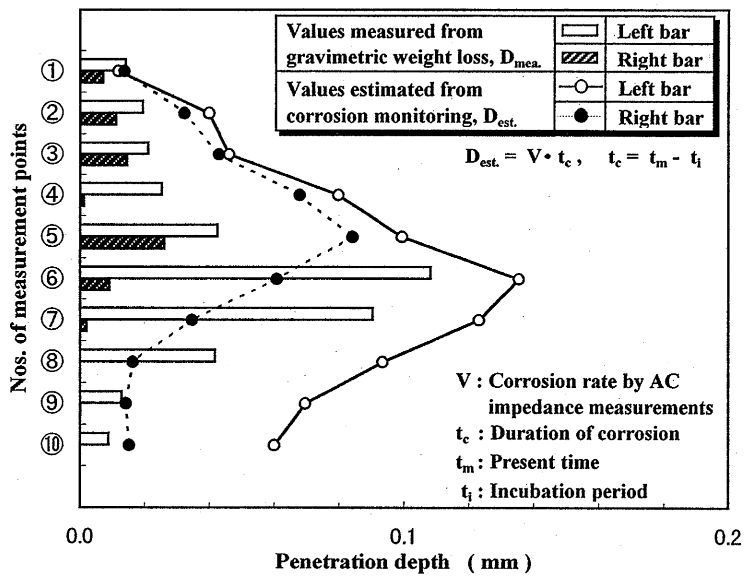

Fig.15 Comparison of amount of corrosion, penetration depth, measured values from gravimetric weight loss, and estimated values from corrosion monitoring

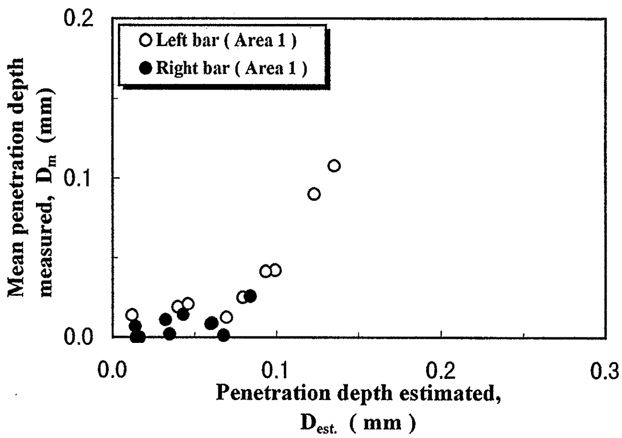

Fig.16 Relationship between penetration depth measured from gravimetric weight loss and that estimated from corrosion monitoring

5. CONCLUSION

Using a newly developed corrosion rate meter, a field investigation was carried out on real concrete structures. The results obtained are as follows.:

- The reinforcement corrosion rate meter provides valuable information on the development of steel corrosion where no external damage is visible.
- Corrosion rates estimated by the new device are superior to the half-cell potentials as an index of corrosion.
- The new technique enables the detection of steel corrosion (Corrosion rate value, Icorr, $>$0.0015mm/year).
- The corrosion penetration depth of reinforcing steel bars was estimated from the product of corrosion rate and the corrosion period, as determined from the diffusion rate of chloride ions. Penetration depth values estimated in this way from corrosion monitoring results correlate well with those measured by a gravimetric weight loss method.

6. ACKNOWLEGMENTS

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7. REFERENCES

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