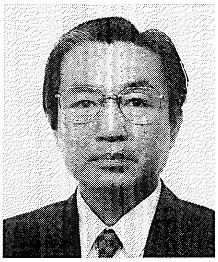
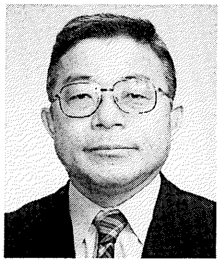
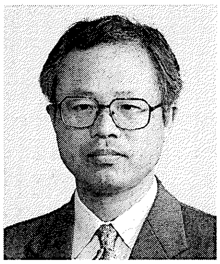
DETERIORATION PROCESS AND ESTIMATION OF DURABILITY OF REINFORCED CONCRETE BEAMS IN LONG-TERM EXPOSURE TO MARINE ENVIRONMENT

(Translation from Proceeding of JSCE, No.613/V-42, February 1999)

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Reinforced concrete beams of several types were placed in the splash zone at three locations on the Sea of Japan, the Seto Inland Sea, and the Pacific Ocean. Changes in the beams, including corrosion of the reinforcing steel, were investigated using electrochemical methods. Although corrosion of the reinforcing steel could not be precisely measured using the half-cell potential method, the characteristics of deterioration and change can be clearly observed when the results of polarization resistance and current flowing between pairs of steel bars are also considered. These 10-year exposure tests have shown that the deterioration of reinforced concrete is influenced by characteristics of the concrete as well as the marine environment.

Key Words : *reinforced concrete beam, marine environment, deterioration process, durability, exposure test, non-destructive test, destructive test*

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1. INTRODUCTION

The durability of concrete structures under marine conditions is, aside from factors such as wave pressure, mechanical abrasion, and loading beyond member capacity, influenced by the penetration/diffusion of chloride ions from sea water. Chloride ions which invade concrete can be separated into those which are fixed by the cement and those which remain free. The presence of many free chloride ions lead to steel corrosion [1]. The penetration/diffusion of chlorides into concrete is influenced internally by various factors and also externally by the action of the sea at the point where the structure is located.

With regard to salt damage to concrete structures, simple methods for dealing with the complicated process of durability can be categorized as follows.
Methods that entail estimating concrete deterioration from weather factors in the marine environment [2] by grasping the movement of chloride ions into the concrete [3], and examining the relation between chloride ions and corrosion of the reinforcing steel [4],[5] are available. On the other hand, various non-destructive methods [6] are used for examining the deterioration of structures, and the application of these to marine structures is widespread. However, with regard to modeling, applicability to the environment must be examined and non-destructive techniques must be evaluated [7]. Moreover, there are extremely few reports in which long periods in actual marine environments are studied.

In this work, reinforced concrete beams of several types were placed in different marine environments and changes in the beams over a 10-year period were investigated by non-destructive methods. This report consists of the results of non-destructive measurements over time and the results of ultimate destructive tests.

2. CORROSION MONITORING FOR SALT DAMAGE

As noted above, the deterioration of marine concrete structures is caused mainly by salt as chloride ions in the sea water penetrate/disperse in the structure. The penetration rate of these chloride ion may be accelerated further by the influence of carbonation and other ions in sea water.

The process by which a sound structure loses performance under salt attack can be divided into the four stages explained as follows.[8]
In the 1st stage, chloride ions accumulate in proximity to the steel, and chloride diffusion speed dominates (the incubation stage). In the 2nd stage, the steel begins corrode under the influence of chlorides and cracks appear in the cover concrete as a result of expansive stress caused by corrosion products. This stage is dominated by the provision of dissolved oxygen and moisture, and by the electric resistance of the concrete (the progression stage). The 3rd stage is when corrosion speed accelerates as a result of cracking in the longitudinal direction and peeling-off of the cover concrete. It is similar to the 2nd stage as regards corrosion factors and is influenced by the load (the acceleration stage). When deterioration reaches the 4th stage, the steel corrodes rapidly and reduces the cross-sectional area of steel, resulting in rapidly declining load performance. It is similar to the 3rd stage (the deterioration stage).

In general, a unsound structure is confirmed as the salt damage reached to the 3rd or 4th stage after occurrence of longitudinal cracks along the reinforcing steel. At this point, even if repairs are carried out, there may be problems of cost and lifetime added. The corrosion monitoring carried out in this study consisted of measuring the half- cell potential, the polarization resistance, the concrete resistance, and the electric current between pairs of reinforcing steel bars.

These measurements are one way to evaluate the corrosion rate of steel non-destructively. They are particularly effective for estimating the corrosion rate and cross section decline in the deterioration process of the 3rd and 4th stages and for predicting the remaining service lifetime of a structure. This is also an effective method of grasping the condition of steel in the concrete at the 1st and 2nd stages non-destructively. These methods of monitoring deterioration will become more important in the future as methods of maintenance/control for established structures.

3. EXPERIMENTAL OUTLINE

3.1 Test Specimens and Factors

Table 1 Materials, mix proportions, and factors

Materials	Cement : Blast-furnace slag cement (B-type) Aggregate : Coarse (Gmax : 25 mm, F.M. : 6.88, ρ : 2.64) Fine (F.M. : 2.90, ρ : 2.59)
Mix proportions	Water-cement ratio (W/C) : 60 %, 40 % Unit water weight : 150 kg/m^3 Unit cement weight : 250 kg/m^3 (W/C : 60 %) 375 kg/m^3 (W/C : 40 %) Air volume : 6±0.5 % Slump : 6 cm
Reinforcing steel	Mild steel with mill scale : D10, SD30 Depth of cover : 25 mm, 50 mm
Lining (Coating)	Non-lined Lined : Epoxy (350 μm) Epoxy+glass cloth (800 μm) Epoxy+glass flake (600 μm) Vinylester (350 μm) Polyurethane (350 μm)
Pre-cracks	Non-cracked Pre-crack : 0.2-mm width

The materials, mix proportions, and experimental factors used in the experiments are shown in Table 1. B-type cement using blast furnace was adopted, while the aggregate was river gravel of maximum size 25 mm and river sand. Although several kinds of reinforcing steel were used in the exposure tests, this report gives the results for mild steel (deformed bars with mill scale) only. The standard water-cement ratio (W/C) of the concrete was 40% for durability under a marine environment, and 60% specimens were made in order to compare with the standard case. The unit water weight was 150 kg/m^3 and the two unit cement weights were, respectively, 250 and 375 kg/m^3. The slump and air volume of the concrete were, respectively, 6 cm and 6±0.5%. The concrete cover over the reinforcing steel was 25 mm and 50 mm.

Specimens with coating specifications ("lining" or "lined concrete") and specimens without coating ("conventional concrete" or "non-lined concrete") were prepared. To compare with conventional concrete, for the lining, different specifications such as epoxy, epoxy-glass cloth, epoxy-glass flake, vinyl ester, and polyurethane were used. Some of the specimens (with the standard 40% W/C) were made with pre-cracks of about 0.2 mm at the center. Two test specimens were made for each factor. The basic form of the test specimens and an outline of measurements are shown in Figure 1.

3.2 Selection of Exposure Location

In the selection of exposure locations, so as to examine the influence of marine environment conditions on the reinforced concrete, three different marine environments were chosen in the Kansai region of Japan (**Figure** 1): the Sea of Japan (Obase district), the Seto Inland Sea (Nishioka district), and the Pacific Ocean (Udono district). Each location is within the splash zone according to the marine environment classification[9] with a separation from the water of close to 0 m. The conditions at each selected marine environment are as follows.

(1) Obase district, Maizuru City: This district faces the Sea of Japan, and the marine weather conditions, particularly in winter, are severe, but the tidal change is small.

(2) Nishioka district, Akashi City: This district faces the Seto Inland Sea, where marine weather conditions are mild but the tidal range is large.

(3) Udono district, Kumano City: This district faces the Pacific Ocean, and the marine weather conditions are severe, but warm.

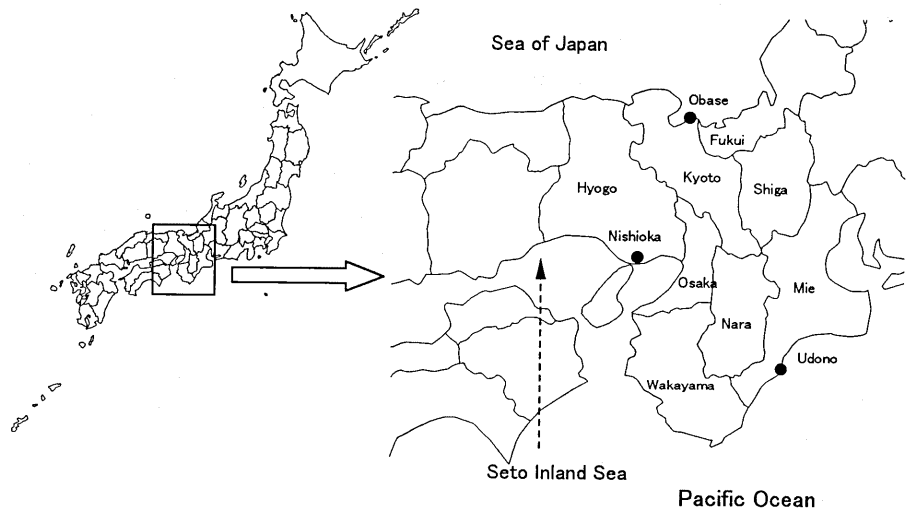
The main environment factors in each neighborhood are compared below (Sea of Japan: Suruga; Seto Inland Sea: Kobe; and Pacific Ocean: Owase)[10]. Comparing the averaged annual air temperature, the Sea of Japan is 14.8℃ and the other two districts are 15.6℃. The Pacific Ocean is about 1℃ lower than the Sea of Japan in July and August, whereas in other months the Seto Inland Sea and the Pacific Ocean are 1-2℃ higher than the Sea of Japan. As for the sea temperature, the Sea of Japan is 11-12℃ in February whereas the other districts are 15-17℃, so the sea temperature difference is more pronounced than the difference in air temperature. As for the averaged monthly relative humidity, the Sea of Japan is about 10% higher in winter than the other districts and the Pacific Ocean in summer is more humid than the other districts. As for precipitation, the Sea of Japan has most in winter, while the Pacific has extremely high precipitation in summer. Therefore, of all these environments, the Pacific Ocean can be seen as the generally warmer and more humid environment than the Seto Inland Sea and the Sea of Japan.

3.3 Measurements and Factors

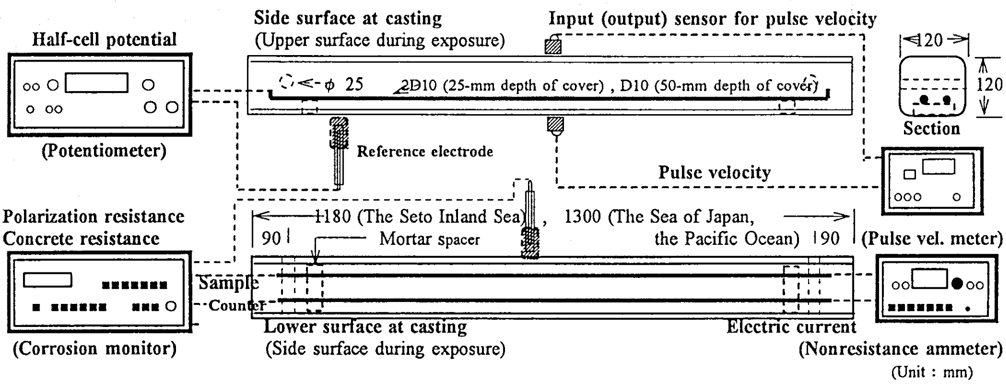
As shown in **Figure** 1, test specimens were laid at the chosen sites with the bottom face at casting to the side and with the two ends facing seaward and landward. Non-destructive tests were done using pulse velocity (to obtain an index of concrete quality), half-cell potential, polarization resistance, and electric current flow (for corrosion monitoring of the reinforcing steel).

Pulse velocity was measured at three positions on each test specimen, at the center and at locations 200 mm toward each end. Input and output pendulum sensors were symmetrically arranged at right angles to the longitudinal axis.

Half-cell potential was measured at intervals of 100 mm from end to other end of cover concrete surface. A three-electrode corrosion monitor was used to measure polarization resistance. The polarization resistance and concrete resistance of all reinforcing steel were measured by the rectangular wave electric current polarization method (100 μA, 0.1Hz, 0.8kHz). A copper/copper sulfate electrode was used as the reference electrode, and a reinforcing steel bar not in use as the sample pole was used as a counter pole. Also, the current between reinforcing steel bars was measured 10 seconds after short circuit using a nonresistance ammeter.



(a) Exposure locations in the Kansai region of Japan



(b) Measurement methods and basic form of test specimens

Figure 1 Exposure locations, measurement methods, and basic form of test specimens

All measurements of coated (lined) test specimens were also carried out excepting half-cell potential; however, the lining layer was not removed at measurement.

After 5 years of exposure, bending tests were done with a 900 mm support span and a 200 mm bending span. In the same test specimens, the chloride ion concentration after 5 years was measured by the potentiometric titration method after cutting the sample. To eliminate influence from the edge face, the specimen was cut mainly about 150 mm along the long axis, about 40 mm along the short axis, and about 10 mm depth (0-10 and 10-20 mm) from the surface. An experimental outline is given in Figure 2.

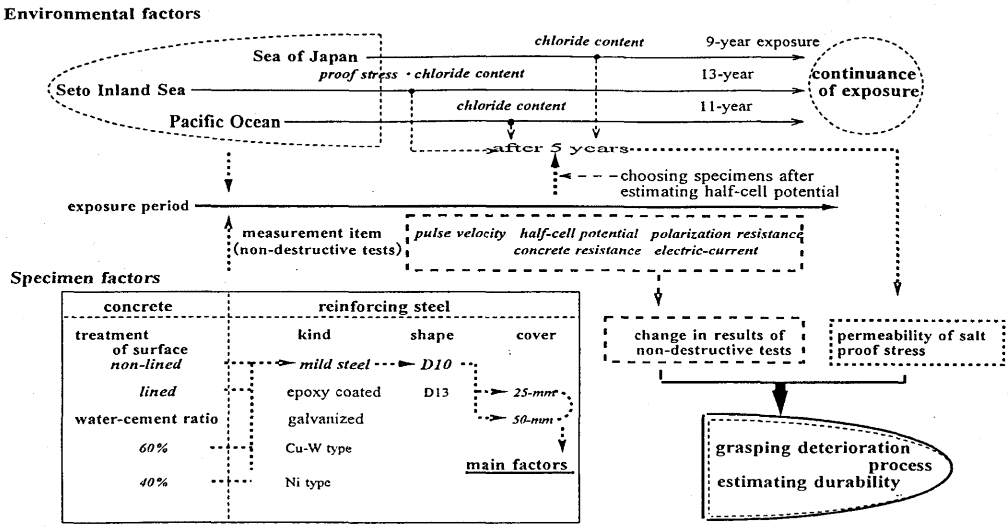


Figure 2 Relation between experimental factors and evaluation methods

4. RESULTS AND CONSIDERATION

4.1 Changes in specimen

a) Visual inspection

Visual inspections consisted of looking for roughness/cracking on the concrete surface, and cracking/swelling/peeling of the lining layer. The roughness of the concrete surface was observed in the test specimens placed at the Sea of Japan and the Seto Inland Sea at 1 year because they were influenced by the sea weather and mechanical abrasion by tides. The roughness of the test specimens at the Pacific Ocean location was also observed. This is because of the influence of waves in stormy weather and the severity of sea weather, such as rainfall, at this site. Changes in the lining surface at each location were observed as discoloration and hairline cracking, although there was no obvious swelling/peeling. Longitudinal cracks caused by steel corrosion were almost absent, while cracking at the reinforcing steel spacer section near the ends was observed in some specimens. This might be considered a failure of adhesion between the mortar spacer and concrete.

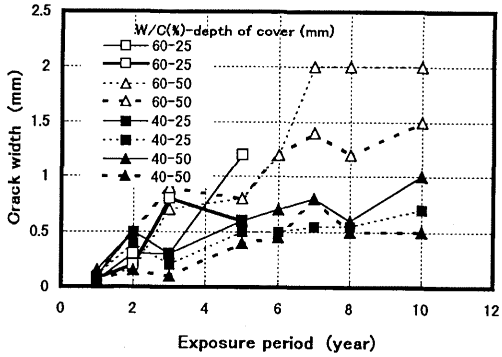


Figure 3 Change in crack width of specimens (Seto Inland Sea)

No notable rust flow from these cracks nor swelling of the concrete due to the cracks was observed. The main reason for this cracking is difficult to judge; it may have been long-term wave exposure, shrinkage of the concrete, or corrosion of the reinforcing steel. Figure 3 shows the change in representative crack widths for test specimens exposed at the Seto Inland Sea. The crack width reached 2 mm due to adhesion failure between the mortar spacer and concrete.

b) Pulse velocity

Changes in pulse velocity are shown in Figure 4. Although the pulse velocity just after exposure at the Seto Inland Sea location was little different among test specimens at about 4km/s, in some specimens, the pulse velocity then decreased. In particular, the 60% water-cement ratio concrete without lining fell to about 3 km/s after 5 years of exposure. In general, the decline in the pulse velocity is influenced by quality or cracks of concrete. However, the decline was resulted from the worse contact of the input/output sensor cause of the concrete surface roughness.

Some specimens in which a pre-crack had been formed at the center exhibited decreasing pulse velocity, but except in such particular cases, cracks were not observed near each measurement point. Test specimens that showed a decline in pulse velocity were rare, while the pulse velocity average up to 11 years of exposure maintained a value of about 4 km/s in most cases and no decline in pulse velocity was observed with a 40% water-cement ratio or lining. Also, since pulses do not pass through the reinforcing steel, there is no influence from the reinforcing steel.

On the other hand, no decline in pulse velocity was observed for specimens at the Pacific Ocean and Sea of Japan locations. Thus, from the results of all pulse velocity measurements, including those for specimens exposed at the Seto Inland Sea location, it can be said that the quality of the concrete declined in just a few of the specimens.

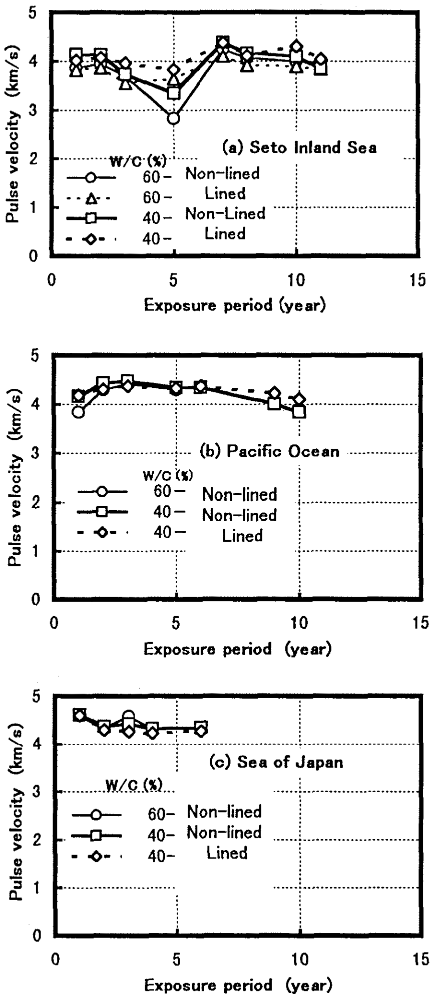


Figure 4 Changes in pulse velocity

c) Changes in half-cell potential

In 60% and 40% water-cement ratio specimens without lining, mild steel bars were arranged with 25-mm or 50-mm cover concrete. The results of half-cell potential measurements are shown in Figure 5 (a)～(c) and the changes in major values of half-cell potential are shown in Figure 6 (a)～(c).

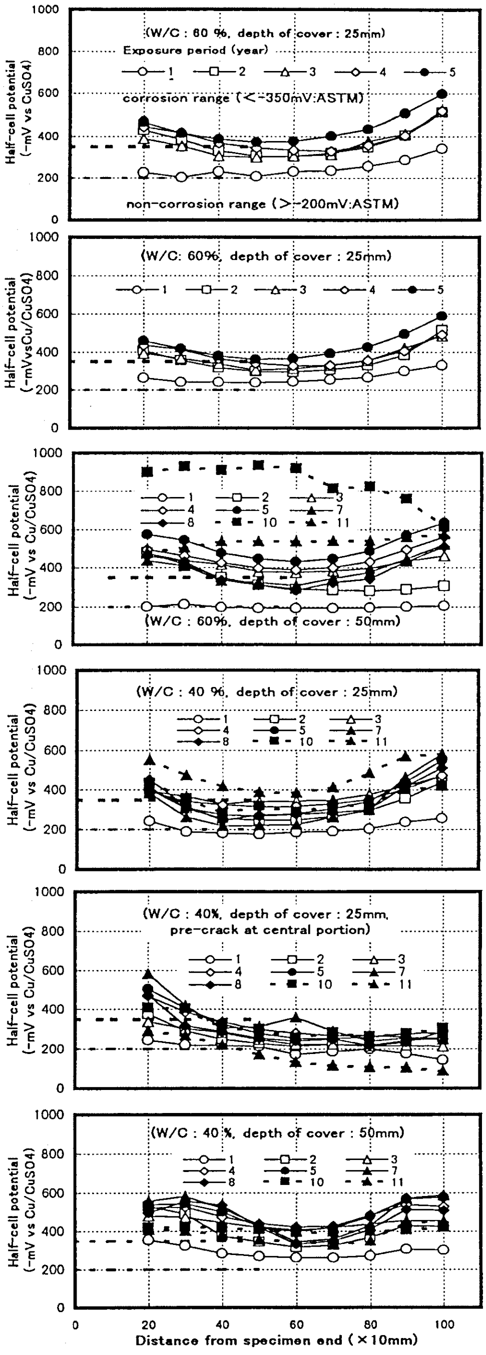


Figure 5 (a) Changes in half-cell potential
(Seto Inland Sea location)

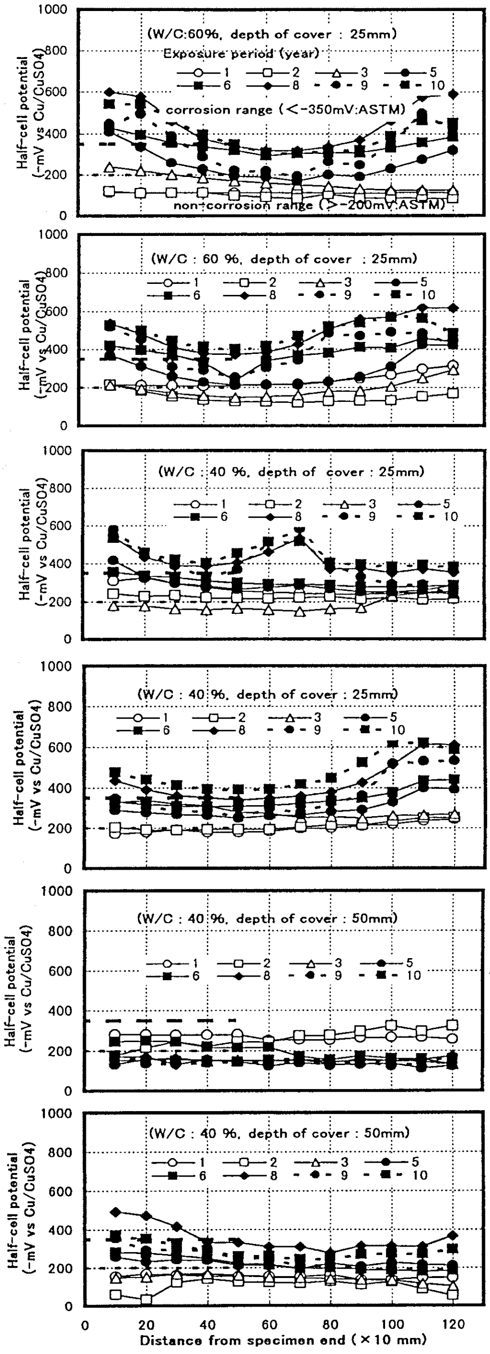


Figure 5 (b) Changes in half-cell potential
(Pacific Ocean location)

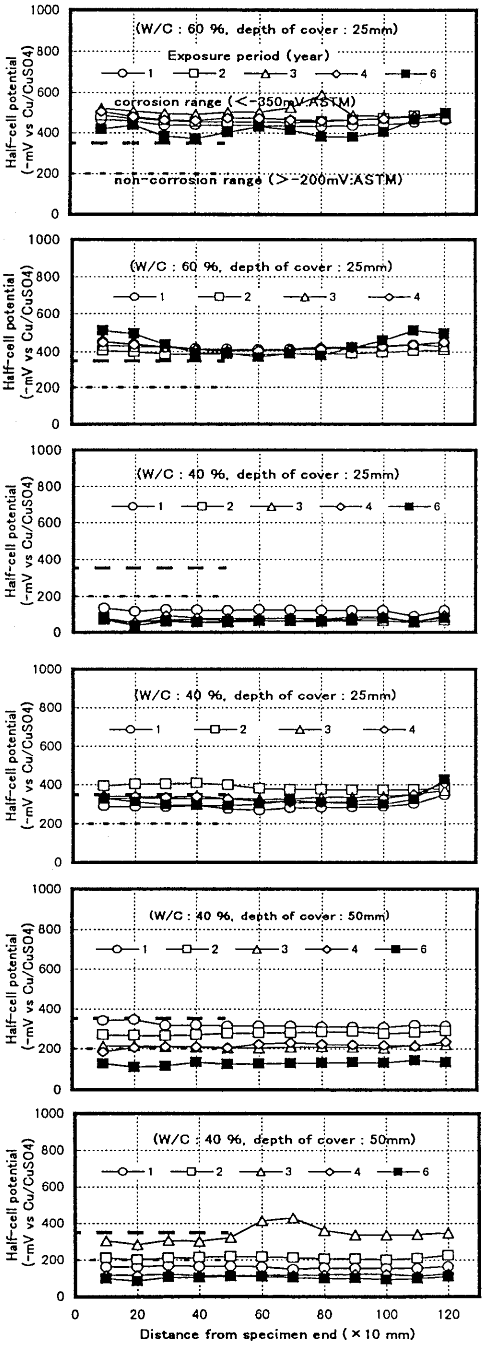
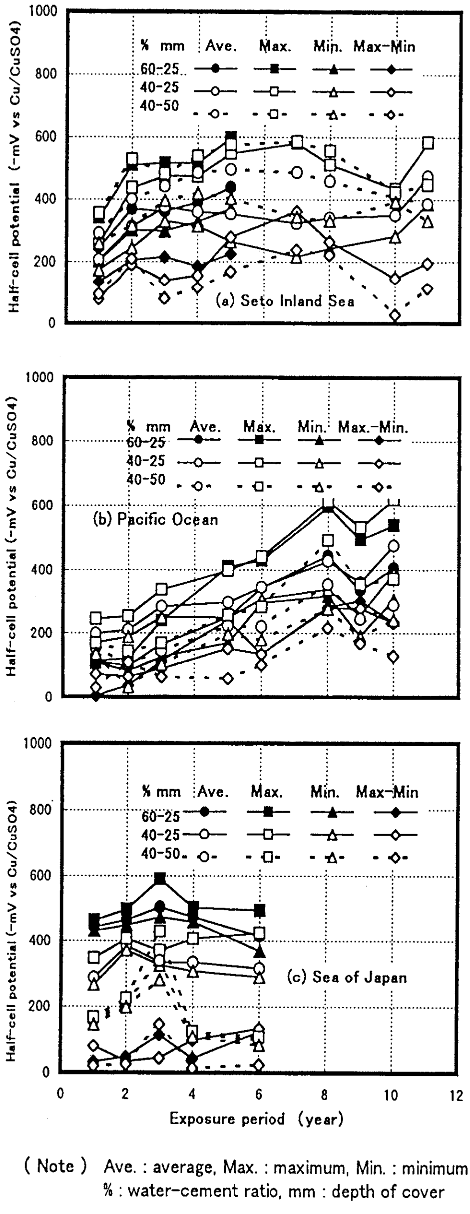


Figure 5 (c) Changes in half-cell potential (Sea of Japan location)



(Note) Ave. : average, Max. : maximum, Min. : minimum
% : water-cement ratio, mm : depth of cover

Figure 6 Changes in major values of half-cell potential

After 1 year of exposure, the half-cell potential of most specimens was about -200 mV and the distribution of values was flat. These half-cell potentials are on the boundary between the non-corrosion range (>-200mV) and the indefinite range (-350~-200mV: between the non-corrosion and the corrosion(<-350mV)) according to ASTM[11] and all reinforcing steel was judged to be almost uncorroded. The values decreased with the elapse of years. In half-cell potential, the period of reaching to the corrosion range (<-350mV) may depend on each factor of specimen.
Comparing the half-cell potential, many values at both ends were lower ("base") than values neighboring the center in specimens. This is because adhesion between the mortar spacer and concrete failed and the penetration/diffusion of chloride ions into this portion became faster than into the high-density portion. Thus, this portion which changed for the base became the anode of a macro-cell corrosion system.

Changing with base at the center of some specimens was not observed at the early stages of exposure. Here, no large cracks are observed and it becomes the anode for exposure period although it is not possible to specify an influence factor. Comparing specimens with the same exposure period and same cover depth, the half-cell potential of 40%-W/C concrete was nobler than that of 60%-W/C concrete. Thus, a low water-cement ratio can protect concrete against reinforcing steel corrosion better than a high water-cement ratio.

No marked advantage of 50 mm cover depth as regards inhibiting corrosion was observed as compared with 25 mm. Even for the same water-cement ratio, and when pre-cracks were introduced at the center, a few change for base were observed after several years of exposure just as in specimens without cracks. However, no marked base value as near the mortar spacer was observed.
In general, partial flaws like cracks have the possibility of promoting the corrosion rate, but it is known that the influence of cracks becomes small when the exposure period is long [12]. From the overall results, it is clear that the half-cell potential decreased with the years of exposure. In particular, the half-cell potential fell markedly from the first year to the second at the Seto Inland Sea location. This suggests that a corrosive environment was formed during this period. As to the cause of this, a more detailed examination will be necessary. [13]

Except in the case of some specimens, no marked change like that at the early exposure period was observed, but as regards the reinforcing steel it is estimated from the half-cell potential that all specimens were in the state between indefinite and corrosion.
Also, the maximum difference (difference between the most noble potential and the most base potential) increased for several years, suggesting that macro-cell corrosion progressed for such a period. On the other hand, the half-cell potential at the Pacific Ocean and Sea of Japan locations moved slightly in the base direction early in the exposure period, just like with the Seto Inland Sea specimens.
At the Pacific Ocean location, the half-cell potential at the ends of a specimen decreased just as with specimens at the Seto Inland Sea location, although this decline tendency was not observed at the Sea of Japan location. Also, the half-cell potential values in both locations are mostly noble than the values at the Seto Inland Sea location.

d) Polarization resistance and concrete resistance

In general, when reinforcing steel is uncorroded, the polarization resistance is high, and the value decreases with increasing corrosion rate. Changes in polarization resistance and concrete resistance are shown in Figure 7.

In this figure, A-L distinguish between the different kinds of lining, and the two reinforcing steel bars in a specimen are indicated separately by the solid line and the dotted line.

At the Seto Inland Sea location, the polarization resistance of reinforcing steel bars in non-lined concrete fell markedly from the first year to the second. Also, the concrete resistance fell markedly in this period, and conditions equated with the beginning of formation of a corrosive environment in the vicinity of the reinforcing steel bars determined from the half-cell potential result.

The polarization resistance of reinforcing steel in non-lined concrete decreased until 5 years of exposure and some of this resistance was impossible to measure due to the marked increase. In the case of reinforcing steel in lined concrete, the decline in polarization resistance was comparatively less than for that in non-lined concrete although it is not possible to examine this by the half-cell potential.

Thus, a lining over the concrete surface is able to protect against the intrusion of water and chloride ions, and can give protection against corrosion.

In general, the relation between polarization resistance (Rp: $k\Omega \cdot cm^2$) of reinforcing steel per unit surface area S (cm^2) and the corrosive electric current (I_{corr}: A/cm^2) is the formula I_{corr} = K/Rp, and this is used for the evaluation of corrosion rate.

In this formula, supposing 0.026-0.030 [14],[15],[16] for proportional coefficient

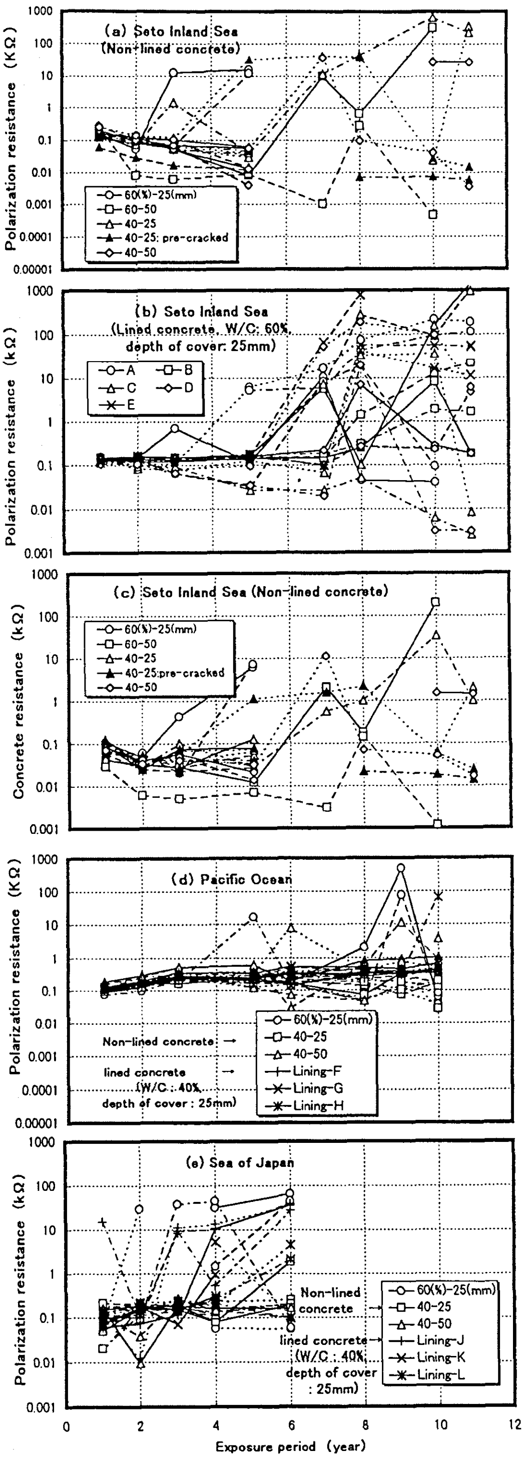


Figure 7 Changes in polarization resistance and concrete resistance

K(V) and using the low value of the measured polarization resistance, the corrosion rate I_{corr} calculates to a large value of more than 10 μA/cm^2. However, it is possible that this result is influenced by the blast furnace slag [13], as was the case with half-cell potential, and this results is influenced by corrosion in the mortar-spacer portion. On the other hand, although the cover is deep, there is a specimen with low polarization resistance. At the initial stage of exposure, large cover has the effect of inhibiting the penetration/diffusion of chloride ions. However, this effect decreases because the greater cover forms a wide electric field that facilitates the corrosion current flowing after the chloride ions had penetrate to a certain degree. Thus, the corrosion rate is mainly affected by the supply of oxygen and by concrete resistance, and if the supply of oxygen is good, the measured value is dominated by the concrete resistance [17] . It is deduced from the result that the resistance of 50-mm cover depth concrete, which formed a wider electric field than the 25-mm concrete, is smaller once chloride ions have penetrated.

At the Pacific Ocean and Sea of Japan locations, the decline in polarization resistance was less than in the non-lined concrete at the Seto Inland Sea location.
Estimating I_{corr} from the polarization resistance as previously described, the corrosion rate of reinforcing steel at the Pacific Ocean and Sea of Japan locations was not particularly large. The difference in polarization resistance at the Seto Inland Sea location as compared with other locations is because of the influence of the environment and because of the influence of the spacer portion.

e) Current between pairs of reinforcing steel bars

The current which occurs as a result of the electromotive force driven by the potential difference between pairs of reinforcing steel bars is generally small in reinforcing steel with a passivity layer, but considerable current flows in steel which has corroded. Changes in the absolute value of this current are shown in Figure 8.

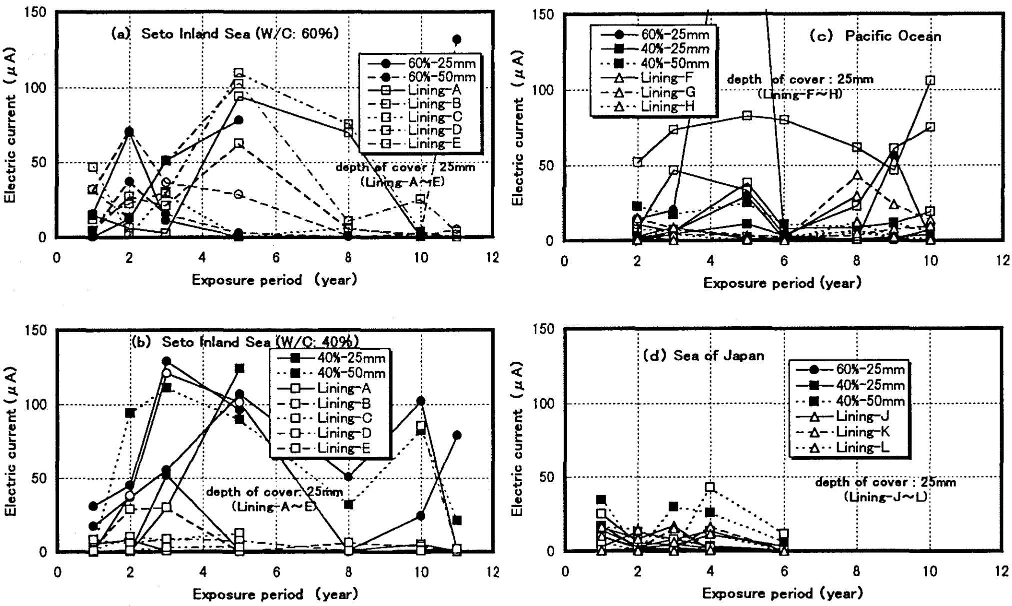


Figure 8 Changes in current between pairs of reinforcing steel bars

Looking at the environmental influence on this current, many specimens exposed at the Seto Inland Sea location show a large current as compared with other marine locations. After two years, although not shown in **Figure 8**, the current flows in the same/reverse direction comparing last year. The reverse current flows are caused by reversing of the anode-cathode pair in the case of macro-cell corrosion. Therefore, the current in the reinforcing steel bar may depend on the corrosion state of each reinforcing steel bar at the time of measurement.
In the case of a 60% water-cement ratio, it is difficult to evaluate the current value in terms of the test specimen factors. In 40% water-cement ratio concrete, the current increased early in exposure in the case of non-lined concrete, and the current of lined concrete was lower than in the non-lined concrete. This result suggests that choosing a low water-cement ratio and adding a lining to the concrete surface is an effective way to protect against reinforcing steel corrosion.

The influence of the lining in the Pacific Ocean location was to yield a small current value, and the current was higher in non-lined concrete, just as for the Seto Inland Sea location. At the Sea of Japan, in the case of most specimens, the current was smaller than at the Seto Inland Sea and Pacific Ocean locations.

4.2 Correlation between Non-Destructive Tests and Reinforcing Steel Corrosion

Some of the specimens at the Seto Inland Sea location were examined physically and analyzed for chloride content after 5 years of exposure. From observation of the reinforcing steel after 5 years of exposure, many specimens had rust near the ends as a result of the influence of mortar spacer adhesion failure, and the half-cell potential at the ends was more base than at other measurement points. However, the relation between the onset of rusting and half-cell potential, and the change in half-cell potential after the reinforcing steel begins to rust cannot be evaluated. A comparison of the half-cell potential at rusted and non-rusted points regarding for corrosion in high probability is shown in **Figure 9**, and the difference in half-cell potential between rusted points and non-rusted ones is about 100 mV.
Although attributable to the influence of blast furnace slag, the potential at rusted points was

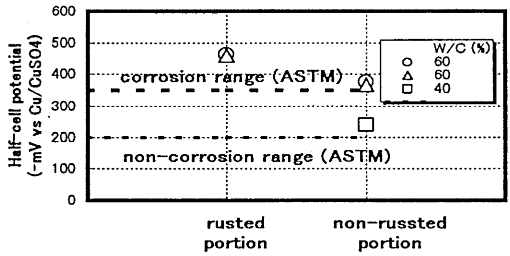


Figure 9 Half-cell potential at rusted and non-rusted portion (Seto Inland Sea, after 5 years of exposure)

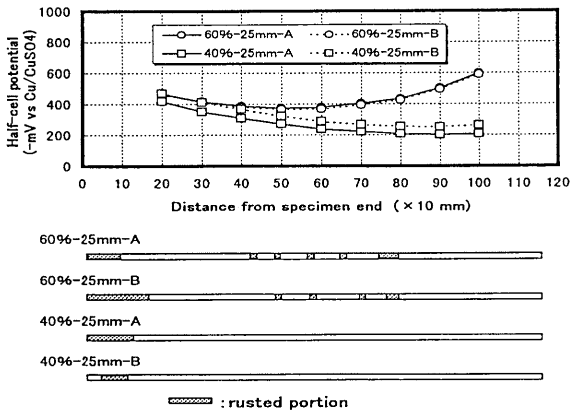


Figure 10 Relation between half-cell potential and reinforcing steel rust (Seto, after 5 years of exposure)

about -450 mV and at non-rusted it was about -350 mV. These values exceed the -350 mV that makes the corrosion region in the ASTM Standard. **Figure 9** compares the potential of non-rusted reinforcing steel (in the 40% water-cement ratio concrete) with the non-rusted part of rusted reinforcing steel, the difference being about 150 mV.
If this difference is assumed to be influenced by the polarization of the anode and the cathode, the actual potential difference is about 250 mV. The shift in the base direction of such an anode is little in the case of a long distance between the rusted portion and the non-rusted portion, and is influenced by the size of the reinforcing steel.
In this case, using the classification given by the ASTM Standard, the relation between the rusted/non-rusted portions and the potential can be evaluated to a certain degree, but it is difficult to estimate the amount of rust by a simple potential classification. Therefore, it is necessary to clarify the difference between the distribution of potential and the change in potential, and to estimate the rusting of the reinforcing steel.
The correlation between half-cell potential and amount of rust in the reinforcing steel is shown in **Figure 10**. Because there is little rust on any specimen, it was judged that the influence of rust on reinforcing steel strength was small.

4.3 Correlation between Chloride Ion Content and Results of Non-Destructive Tests

The total chloride ion content of specimens exposed for 5 years at the Inland Sea, Pacific Ocean [18] and Sea of Japan locations is shown in **Figure 11**. Based on the content of chloride ions (**Figure 11**) as obtained from exposed specimens at the Inland Sea and Pacific Ocean locations, the coefficient of diffusion D and the concentration of chloride ions C (at the surface and near the reinforcing steel) were calculated[19][20]. Calculation results are shown in **Table 2**.
Because the content of chloride ions was measured in the direction of concrete depth from the lower casting surface (the side surface during exposure) and there were two measurement points, rough estimates of D were compared.
D in the two locations was $D_{60\%} \fallingdotseq 6\times10^{-8}$ cm²/s (W/C is 60%) and $D_{40\%} \fallingdotseq 4.4\times10^{-9}$ cm²/s (W/C is 40%) (Seto Inland Sea) and $D_{60\%} \fallingdotseq 4.5\times10^{-8}$ cm²/s and $D_{40\%} \fallingdotseq 5.5\times10^{-9}$ cm²/s (Pacific Ocean). These values of D are not markedly different and are lower than values given in the literature [19] [21]. The concentration of chlorides at the surface C_0 and at neighboring reinforcing steel C_{25} is higher at the Pacific Ocean location than at the Seto Inland Sea location as in **Table 2**. Therefore, as regards the supply of chloride ions, it is deduced that the Pacific Ocean as a splash environment is more severe than the Seto Inland Sea as a tidal environment.

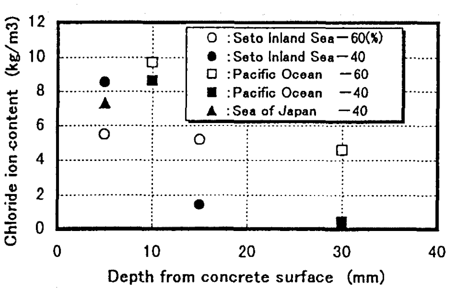


Figure 11 Total chloride ion content

Table 2 Content C and coefficient of diffusion D

		Seto Inland Sea	Pacific Ocean	Sea of Japan
Sur. conc. (kg/m³)	$C_{60.0}$	6.5	12.0	
	$C_{40.0}$	9.4	17.5	(7.3)
Near ste. conc. (kg/m³)	$C_{60.25}$	3.7	6.2	
	$C_{40.25}$	0.3	1.0	
Coefficient of diffusion (cm²/s)	D_{60}	6.0×10^{-8}	4.5×10^{-8}	
	D_{40}	4.4×10^{-9}	5.5×10^{-9}	(5.0×10^{-9})

(Note) Sur. : surface, conc. : concentration, ste. : steel

The surface concentration in 40% concrete at the Sea of Japan is assumed to be 7.3 kg/m^3, which was the concentration at the depth of 0-10 mm, and the coefficient of diffusion is assumed to be about 5×10^{-9} cm^2/s, the value obtained from other districts. Then, in 40% concrete, the concentration C_{25} at the neighboring reinforcing steel is estimated at about 0.4 kg/m^3. If the critical chloride concentration at which the reinforcing steel corrodes is 1.2 kg/m^3-2.5 kg/m^3 [22], then the 60% concrete reached this critical concentration in the Inland Sea and Pacific Ocean, while the 40% concrete remained below the critical concentration in all cases including the Sea of Japan.

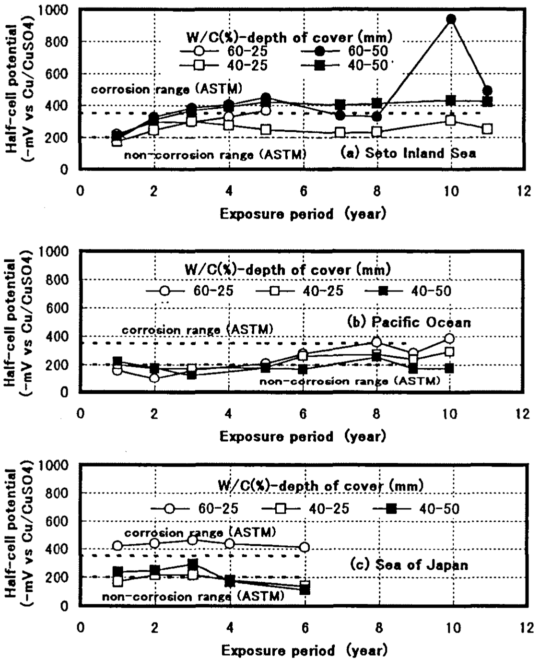


Fig 12 Changes in median value of half-cell potential

On the other hand, changes in the half-cell potential median (the average of 3-4 data points in the center portion where there is little effect of adhesion failure of the mortar spacer) are shown in Figure 12. After 5 years of exposure, the potential of specimens with 60% W/C and 25 mm cover at the Seto Inland Sea and Sea of Japan locations show the corrosion range in the ASTM Standard and the potential for all 40% W/C specimens show almost the non-corrosion range. Therefore, there seems to be an approximate correlation between the micro corrosion environment as caused by chloride ions in the vicinity of reinforcing steel and the half-cell potential.

On the other hand, at the Pacific Ocean location, no correlation between chloride concentration and half-cell potential was indicated. This is because the critical concentration depends on many factors, such as the concrete mix proportion and the environment. [23]

Thus, these factors must be considered when the correlation between chloride concentration and the results of non-destructive measurements is examined.

4.4 Flexural Test

Some of specimens which had been exposed for 5 years in the Seto Inland Sea were subjected to flexural tests. The results are shown in **Table 3 and Figure 13**.

Table 3 shows the results on the various kind of reinforcing steel and **Figure 13** shows only those for mild reinforcing steel. Failure types were divided into bending or shearing, though the yield load was never below the result for an inland specimen after an equivalent exposure period. These results exceed the bending/shearing proof stress which was obtained from calculations, and the performance of these specimens was judged to be undiminished. This finding agrees with the estimate developed from the reinforcing steel corrosion in section 4.2.

Table 3 Result of flexural tests
(Seto Inland Sea, 5 years of exposure)

		Measurement result			Calculation
		Max. load	Yie. load	Bro. Type	
W/C:60% steel:2D10 depth of cover :25mm	A	32.2	27.4	S	With safety coefficent bending :15. 6 shearing :12. 6
	B	30.4	27.6	M	
	C	33.4	27.7	M	
	D	31.9	27.8	S	
	E	30.0	28.0	M	
	F	24.7	24.7	S	
	G	32.9	28.5	S	
	H	31.5	27.9	M	
W/C:40% steel:2D10 depth of cover :25mm	A	31.5	28.6	S	With safety coefficent bending :17. 1 shearing :15. 3
	B	32.3	28.3	M	
	C	33.4	32.1	S	
	D	32.4	28.5	M	
	E	34.1	28.8	M	
	F	32.4	24.5	M	
	G	30.1	28.5	S	
	H	33.1	28.4	M	

(Note) Max. : maximum, Yie : yield, Bro. : broken, S : shearing, M : bending (Unit:kN)

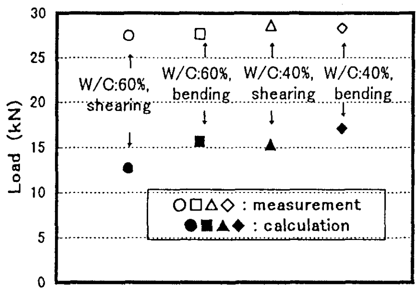


Figure 13 Result of flexural tests on Specimens without lining (from Table 3, mild steel)

4.5 Estimation of Environmental Effect

In this section, the influence of the environment is evaluated by synthesizing each measurement. Synthesizing Figure 12 as described in the section 4.3 for each factor, the half-cell potential is estimated as follows.

Change in half-cell potential, a corrosive environment is formed earliest in case of the Seto Inland Sea if the case of 60% W/C at the Sea of Japan location is excepted, and corrosion at the Sea of Japan and Pacific Ocean locations seems to lag that at the Seto Inland Sea. The cause of this behavior at the Seto Inland Sea location seems to be corrosion induced by mortar spacer adhesion failure at an early stage of exposure or perhaps the repeated wetting and drying conditions due to tides. On the other hand, at the Sea of Japan location, the environment is characterized by repeated wetting/drying and the regular replenishment of chlorides, as at the Seto Inland Sea. However, it seems that 40% W/C concrete displays protection against corrosion.

Comparing 5 and 6 years of exposure, specimens with 40% W/C and 25 mm cover depth indicated a potential at the Sea of Japan location that was in the non-corrosion region; it was nobler than at the Pacific Ocean and Seto Inland Sea locations. Therefore, the corrosion of concrete structures is influenced more by mild climate and tidal environments such as at the Seto Inland Sea location and by mild climate and severe splash environments such as the Pacific Ocean than by conditions at the Sea of Japan location.

The results of the half-cell potential in each environment may contain the adhesion failure of mortar spacer portion. Therefore, environmental effect is evaluated as follows from other measurement results. As regards polarization resistance, the Seto Inland Sea is more severe than the Pacific Ocean and the Sea of Japan, while with regard to the electric current between reinforcing bars, the Seto Inland Sea and the Pacific Ocean are more severe than the Sea of Japan.

The penetration/diffusion of chloride ions indicates that these environments are ordered by severity as follows: Pacific Ocean > Seto Inland Sea > Sea of Japan.

Although these results were obtained from only limited experimental locations, the Seto Inland Sea and Pacific Ocean locations are judged synthetically to be more severe than the Sea of Japan.

Judging from various corrosion monitoring estimates, the process of deterioration in each location is as follows.
(1) Seto Inland Sea: all 60% and 40% W/C specimens are pass through the 1st stage (incubation) at between 1 year and 2 years of exposure, and these specimens are advance to the 2nd stage (development)
(2) Pacific Ocean: all specimen remained in at incubation stage until 5 or 6 years of exposure, and thereafter the 60% specimens reach the development stage and 40% ones remain in the transition period between incubation and development
(3) Sea of Japan: most of the samples remain in the incubation

Although there are differences according to exposure time in each environment and also according to mix proportion, all samples are in or close to deterioration from the 1st stage, incubation, to the 2nd stage, development.

5. EVALUATION OF EACH MEASUREMENT METHOD

All marine environments are within the splash zone, but they differ in factors such as marine weather and actual conditions in each marine environment.
To investigate this subject, differences in the deterioration process of structures under marine environments were examined in this study.
With the pulse velocity method, it was difficult to evaluate differences according to environmental factors, because most specimens showed no decline in pulse velocity although all are likely to be affected markedly by marine weather over the long term.
On the other hand, the results obtained with the half-cell potential tests corresponded to variations in the marine environment and specimens and it was possible to evaluate these variations to a certain degree. Moreover, the judgment that a lining improves protection against corrosion was obtained by measuring polarization resistance, concrete resistance, and electric current.
Thus, these are effective methods for estimating variations in the process of deterioration according to differences in structure factors, such as mix proportion and the presence or absence of a lining. However, further corrosion monitoring and an examination of estimation methods are necessary.

6. FUTURE DEVELOPMENTS IN MARINE EXPOSURE TESTING

The ultimate purpose of estimating durability is to forecast changes of performance that affect service life. To this end, understanding conditions before performance decreases and accurately understanding the cause and degree of the performance decline are main points for right estimating durability.
As shown in **Figure 2**, the experiments described here are continuing at present in all three marine environments. The various experiments described in this report show that deterioration over the exposure period remained mainly the 1st and 2nd stages, as described in section 2.

After examining specimens which had been exposed for 5 years at the Seto Inland Sea location, specimens indicated sufficient proof stress, but the failed by bending and shearing in bending tests. Thus, in terms of performance, the specimens at present are in a condition before a decline in performance becomes apparent.
In the future, it will be necessary to evaluate the bending performance of specimens that from the 3rd stage to the 4th stage described in section 2, and it will consequently be necessary to carry out a comparison by controlling the failure type. [24]

7. CONCLUSION

This report describes part of the results obtained from long-term exposure experiments. The following conclusions were made.

(1) No marked decline in concrete quality was noted from the results obtained with the pulse velocity method.

(2) As regards changes in half-cell potential, 40% W/C specimens tended to become more base at the Seto Inland Sea location while those at the Sea of Japan location became nobler than those at the Seto Inland Sea and Pacific Ocean locations.

(3) The polarization resistance and concrete resistance of specimens exposed at the Seto Inland Sea decreased with exposure period and this means the corrosion rate might have been large, but these results differed if a lining (coating) was applied to the concrete surface. In particular, there was little decline in polarization resistance in specimens with the lining specification, so the lining was shown to be effective protection against corrosion. At the Pacific Ocean and Sea of Japan locations, most specimens showed no decline in polarization resistance over the exposure period.

(4) At the Seto Inland Sea location, corrosion began early in many specimens, as seen by the high electric current in these specimens at an early stage of exposure.
The lining had the same effect as seen with polarization resistance measurements.
At the Pacific Ocean location, some of specimens without lining also exhibited a large electric current. At the Sea of Japan location, the electric current was smaller than in other exposure locations, and there was no marked difference in characteristic according to specimen factors.

(5) Although environmental factors in each marine location were different in the three exposure environments, the severity of environmental action in each can be evaluated by a synthetic evaluation as carried out in this exposure experiment.

(6) The use of a variety of monitoring methods allows effective estimation of the deterioration process of reinforced concrete beams under the action of a marine environment.

Acknowledgements

We would like to thank the Marine Concrete Working Group, which is based on the Wakate Konkurhito Kenkyu-Kai (Young Concrete Engineers Research Group), for help in carrying out this research.
Also, we appreciate the leading of Dr. Manabu FUJII, previously a professor in the Department of Civil Engineering at Kyoto University.

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