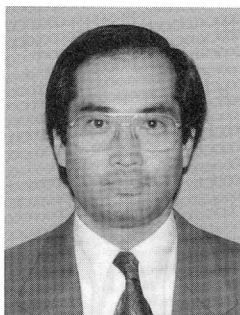


FUNDAMENTAL STUDY ON REINFORCEMENT CORROSION IN CONCRETE CRACKS
DURING SEAWATER SEEPAGE

(Reprinted from Transaction of JSCE, No.466, V-19, 1993)



Tomoji HIRUKAWA



Harumitsu KENBOU



Yoshinori MORI



Yo ITO

SYNOPSIS

This paper concerns the corrosion of steel bars resulting from the permeation of cracks by seawater. This is an important design issue for large, hollow underwater structures. The authors experimentally studied the effects of seawater seeping through cracks on the corrosion of steel bars. An AC impedance technique was used to characterize the corrosion. The corrosion rate varied according to the width of the crack and the seawater flow characteristics.

Keywords : corrosion, crack, permeability, reinforcing bar, concrete, nondestructive test

.....
T.Hirukawa is a general manager at the Otsuki operations office of Nihon Doro Kodan. He graduated from the Gifu University in 1967. He is a highway engineer involved in the design of man-made islands for the Trans-Tokyo Bay Highway from 1990 to 1993.

.....
H.Kenbou is the senior engineer of the 1st Design Department, Civil Engineering Design Division, Kajima Corporation. He graduated with a BSc degree in civil engineering in 1979 from Chuo University, Japan. He joined Kajima Corporation and has worked on the design of ports, oil-tank foundations, and vertical shafts for tunnels.

.....
Y.Mori is a manager in the research and test section of the Technical Division of the Public Works Research Center, Tokyo, Japan. He graduated from the Engineering School of Tokyo's Waseda University in 1951. His research activities are on the corrosion of civil engineering structures and the development of corrosion control techniques.

.....
Y.Ito is an assistant manager at the Technical Research & Development Institute of Kumagai Gumi Corporation, Tokyo, Japan. He received his Doctor of Engineering Degree in 1989 from Hokkaido University. His research interests include the permeability of concrete and reinforcement corrosion.

1. INTRODUCTION

Many large, hollow RC structures have been constructed recently. Commonly, these are massive externally constrained concrete structures which may suffer from thermal penetration of cracks[1]. Under the sea, there is a pressure differential between the inside and outside of a closed structure. This results in a forced penetration of seawater through cracks in the concrete. Corrosion becomes a serious problem when water, salt, and dissolved oxygen penetrate the cracks and come into contact with the steel reinforcing bars.

Many marine concrete structures are of a heavy, solid construction. Such submerged structures are not subject to this type of differential pressure. Accordingly, very few studies of corrosion in underwater structures have considered the effects of forced penetration of seawater into structural cracks.

The purpose of this study is to clarify the process by which steel bars corrode in an underwater concrete structure that is subject to high-pressure seawater permeation. The study focuses on the extent to which pressurized seawater permeates cracks, in an attempt to understand the corrosive environment. The AC impedance technique was used to measure polarization resistance and to determine the change in corrosion rate over time. The authors intend to use the data obtained by this method to set up evaluation parameters for a study of the effects of crack width and seawater flow rate on the corrosion of steel bars. We also include in this paper new data concerning steel bar corrosion in underwater RC structures.

2. EXPERIMENTAL METHOD

2.1 Experimental Apparatus

Two experimental setups, I and II, were used to apply continuous saltwater pressure to an RC structure and thus assess the degree of permeation into the structure. Figure 1 is a schematic diagram of apparatus I, which was able to accommodate a maximum of 18 specimens at pressures between 0.098 and 0.294 MPa. Apparatus II accommodated up to three specimens at pressures up to 0.98 MPa. The high-performance filter cartridge (③ in Figure 1) was of a fiber construction and was able to trap particles of 5 μm or less in diameter. It served to remove suspended solids, such as corrosion products, from the artificial seawater and thereby keep turbidity below a predetermined value. As Figure 1 shows, apparatus I featured a complete water circulation system in which the return pump ⑧ was activated when the reservoir ⑦ filled with water to return water to the artificial seawater tank ①. This enabled continuous application of water to many specimens over a long period.

Photo 1 shows the specimens in apparatus I.

2.2 Preparation of Specimens

The reinforcing material were of two types: surface-polished, round SS400 steel bars 28 mm in diameter and sandblasted, deformed SD345 steel reinforcing bars 29 mm in diameter. After measuring weight and dimensions, one steel bar (two when measuring polarization resistance) was fixed to a form, into which concrete was then poured. The specimens were air cured at

a temperature of 20°C and a relative humidity of 60% for three days.

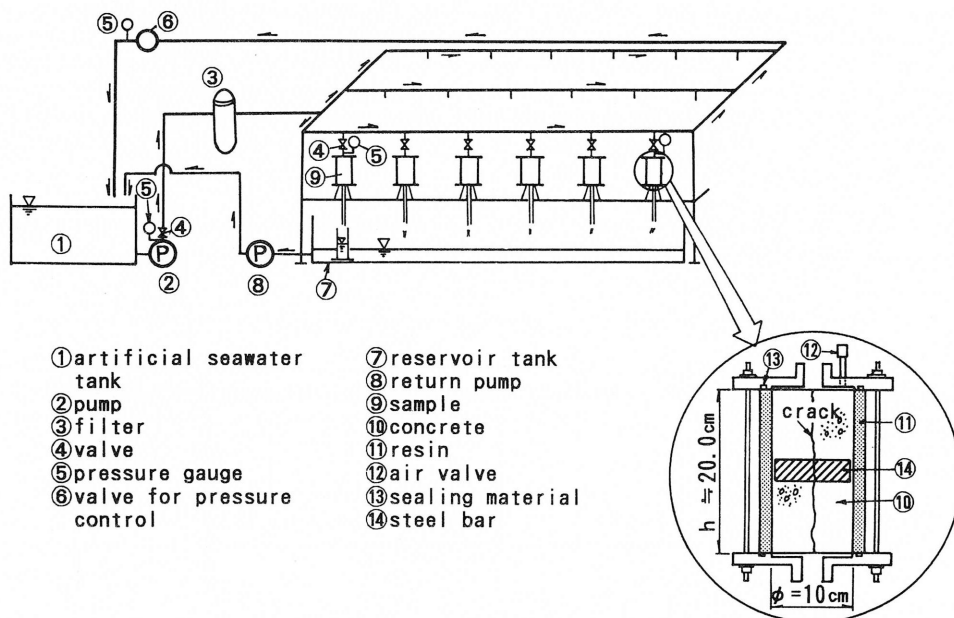


Fig. 1 System of experiment

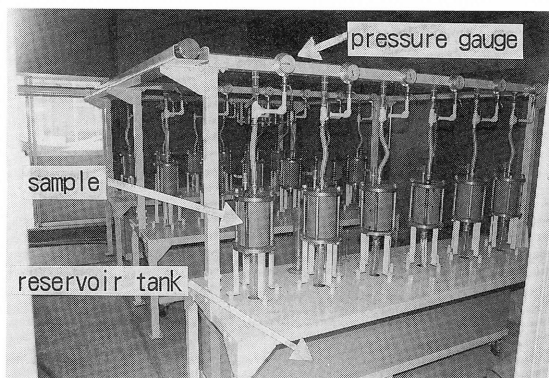


Photo 1 Experimental apparatus

A brass plate was inserted into some of the specimens before the concrete was poured. After three days of air curing, the plate was removed to form a flat crack passing all the way from one end of the concrete block to the other. The entire surface of each of these cylindrical specimens was coated with epoxy resin. After the resin had hardened completely, a diamond cutting wheel was used to cut the 10 cm diameter cylinder to a length of 20 cm with flat ends.

The specimens with no brass plate inserted were cleaved to form cracks

perpendicular to the steel bars. They were of similar size to the flat-crack specimens.

Because of the difficulty in forming cracks by cleavage, 21 of the 50 specimens were suitable for use in the water-circulation test. Just prior to mounting each specimen in a pressure adapter, the width of each crack was measured at nine points on the top and bottom surfaces. After testing, each specimen was cut into five slices, and the top and bottom surface of each slice was examined using a magnifying glass to determine crack width. The average of all these measurements was taken to determine the nominal width of each crack.

Table 1 shows the chemical composition and other properties of the concrete used in this experiment. The cement was ordinary portland cement.

Table 1 Mix proportion of concrete

nominal strength f'_{ck} (MPa)	G_{max} (mm)	slump (cm)	air (%)	W/C (%)	s/a (%)	unit weight (N/m ³)				
						C	W	S	G	AE
26.46	25	4 ± 1	4 ± 1	55	38	2452	1353	7619	12473	18.3

2.3 Experimental Method

(1) Corrosion of steel bars after permeation of seawater through a crack

The artificial seawater was a mixture of 245 g of NaCl, 111 g of MgCl₂·H₂O, 41 g of Na₂SO₄, 12 g of CaCl₂, and 7 g of KCl in 10 liters of water. The tank in apparatus I initially contained about 2.4 m³ of this artificial seawater. Apparatus II initially contained about 80 liters. After switching on the circulation pump, the pressure control valve ⑥ was used to adjust the pressure of the circulating water. The maximum pressure was about 0.294 MPa for apparatus I and about 0.98 MPa for apparatus II. At this point, valve ④ just above each specimen was opened to begin the application of pressure to the specimen. Air valve ⑫ was then opened to bleed air between the specimen's upper face and the attachment. Valve ④ was also used to adjust the water pressure at the upper face of each specimen.

While the test was in progress, leakage, polarization resistance, and other characteristics (concentration of salt, concentration of dissolved oxygen, turbidity, temperature, and pH) were measured. After a predetermined length of time (two, four, or twelve months), specimens were removed from the apparatus and dismantled to remove the embedded steel bars. After a visual inspection, the corrosion ratio of the bars — based on the measured area of corrosion — and the corrosion rate as calculated from the measured change in diameter were determined. The corrosion rate was related to the crack width and the flow rate of water permeating the crack.

(2) Corrosion of steel bars in stagnant seawater

Specimens were submerged in the unpressurized seawater tank of apparatus I for a predetermined length of time (two, four, or twelve months), and then examined in the same manner as above.

(3) Corrosion of steel bars during repeated wetting and drying

Tests of four wetting/drying cycles were conducted at a pressure of 0.294 MPa with apparatus II. One cycle consisted of a one-week wetting period (seawater flow) and a one-week drying period (air curing). Upon the completion of one test lasting eight weeks, the specimens were examined in the same manner as above.

(4) Measurement of polarization resistance

The AC impedance method was used to measure the change over time of polarization resistance, R_p , and seawater resistance, R_s , in certain specimens[2]. Figure 2 shows the polarization resistance monitoring system used during these measurements. The two steel bars served as electrodes. As shown in the figure, the equivalent circuit of this measurement system consists of polarization resistances R_{p1} and R_{p2} , capacitances C_1 and C_2 , and the electrical resistance of the seawater R_s . Components R_{p1} (R_{p2}) and C_1 (C_2) are in parallel, and are connected in series by R_s . In this case, the total polarization resistance, R_p , detected by a corrosion monitor might be expressed as $R_p = R_{p1} + R_{p2}$. The value of R_s varied according to the amount of seawater contained in the crack and the amount of concrete between the electrodes. The corrosion ratio is inversely proportional to R_p . The electrical resistance of the seawater in the crack should increase as R_s rises.

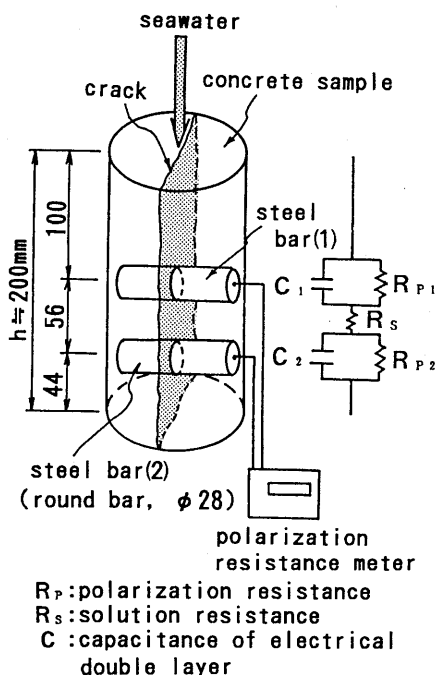


Fig. 2 Monitoring system for polarization resistance

Table 2 Experimental cases and flow conditions

specimen No.	type of bar	type of crack	crack width (mm)	pressure (MPa)	test period	
I-A-1	deformed bar(D29)	rough	0.17	0.294	2 months	
I-A-2			0.33			
I-A-3			0.25			
I-B-1	round bar (φ 28)	rough	0.14	0.294		2 months
I-B-2			0.36			
I-B-3			0.65			
I-C-1		flat	0.51	0.098	4 months	
I-C-2			0.61			
I-C-3			0.92			
I-D-1			0.51			
I-D-2			0.64			
I-D-3		0.90	0.294	0.294		2 months
I-E-1		— — — — —				
I-E-2	0.26					
I-E-3	rough	0.36	0.98	2 months		
II-A-1		0.14				
II-A-2		0.42				
II-A-3		0.80				

*) specimen for chemical analysis

2.4 Experimental Conditions

Table 2 shows the experimental conditions under which continuous pressure of seawater was applied. The capital letters I and II represent the apparatus used in each experiment. Two types of steel bar (round bars 28 mm in diameter and deformed bars 29 mm in diameter) were used, along with two types of crack (rough and flat), two levels of water pressure (0.098 ~ 0.294 MPa and 0.98 MPa), three crack widths (ranging from 0.1 to 1.0 mm), and two exposure periods (two and four months). All other conditions (concrete composition, seawater composition, crack length, etc.) were constant. Note that the water pressure in the flat cracks was not 0.294 MPa but 0.098 MPa because excessive leakage and permeability made it impossible to maintain the set pressure of 0.294 MPa. A water pressure of 0.29 MPa corresponds to a depth of about 30 m, and 0.98 MPa corresponds to a depth of about 100 m.

Twenty-one specimens were subjected to the continuous application of pressure and three specimens were used in the repeated wetting and drying experiment. The immersion test involved 25 specimens: three for the two-month span, seven for the four-month span, and 15 for the 12-month span. As shown in Table 3, polarization resistance measurements were conducted on nine specimens: I-F-1 through -3 (those used in the 12-month exposure to pressurized seawater); S-1 through -3 (as used in the 12-month immersion experiment); and II-B-1 through -3 (those subjected to repeated wetting and drying).

Table 3 Experimental cases for corrosion monitoring

Table 4 Results of environmental conditions

test condition	specimen No.	crack width (mm)	pressure (MPa)	polarization resistance R_p (k Ω)	corrosion rate ($\times 10^{-4}$ mm/y)	test period	measured item	marked value	average measured results		related phenomena	seawater environment of Tokyo bay
									apparatus I	apparatus II		
seawater flow in a crack	I - F - 1	0.09	0.294	0.236	0.60	12 months	temperature	under 50℃	27.2 ~ 41.0 ℃	45.0 ℃	corrosion seepage	8 ~ 20 ℃
	I - F - 2	0.35		0.070	0.15		turbidity	under 4.0ppm	0.15 ~ 0.51 ppm	0.16 ppm	seepage (clogging)	2 ~ 7 ppm
	I - F - 3	0.36		0.105	0.50		concentration of salt	order of 3.27%	2.80 ~ 3.15 %	3.06 %	corrosion seepage	order of 3.0 %
submerged in seawater	S - 1	0.14	—	0.116	0.15	12 months	concentration of dissolved oxygen	order of 6.0ppm	4.20 ~ 4.64 ppm	4.38 ppm		3.0 ~ 9.8ppm
	S - 2	0.36		0.233	0.20		pH	under 9.5	7.89 ~ 8.20	8.15		7.9 ~ 8.4
	S - 3	0.48		0.252	0.35							
seawater flow and air curing cycle	II - B - 1	0.06	0.294	—	7.00	2 months						
	II - B - 2	0.12		—	6.90							
	II - B - 3	0.28		0.151	5.30							

* 1 : $R_p = \{ \int (R_p) dt \} / T$. T : test period

3. Results and Discussion

The results obtained in the experiments detailed above are in this section discussed as regards the effect of water permeation on the corrosion of steel bars. The results of the polarization resistance measurements will be discussed separately, since these experiments involved specimens containing two steel bars.

3.1 Experimental Conditions

Experimental conditions were measured as described in Section 2.3(1). Table 4 gives a comparison between the measured values and the target values. The target values were set in accordance with those found in actual situations. The target value of seawater temperature was made considerably higher than normal sea temperature because the significant frictional heat generated by circulation of the high-pressure water had to be considered. This effect is likely to have promoted slight corrosion[3]. Because the measured turbidity values were so small, it is assumed that corrosion products were removed from the seawater. Measured salinity was within the set range of target values. Measured concentrations of dissolved oxygen were somewhat low as a result of the higher temperatures. This would have retarded corrosion, probably by 10% to 20%[3]. Measured pH levels were lower than the target value, but would have had an insignificant effect on the corrosion rate, since corrosion rates do not change in a pH range of 5 to 9.5. Thus the actual experimental conditions were generally close to the target values, and no correction or adjustment of the corrosion rates as calculated from measured values was carried out.

3.2 Seawater Leakage

Figure 3 shows typical results of seawater leakage. Measured leakage values q have been converted to the values at 20°C. "i" in this figure represents the hydraulic gradient. In Result (a), the leakage rapidly decreases to a very small steady value, and then nearly stops. The crack was a cleavage 0.17 mm in width. Clogging is a possible cause of such a rapid decrease. The specimens were dismantled to allow analysis of the clogging materials and deposits on the crack walls by electron probe microanalysis, X-ray diffraction, and chemical analysis. The materials were found to be low-solubility materials [mostly CaCO_3 and $\text{Mg}(\text{OH})_2$] presumably formed by the reaction of components of the concrete with components in the seawater. CaCO_3 was probably formed by the reaction of the large numbers of Ca^{2+} ions in the artificial seawater or cement with CO_3^{2-} ions contained in the seawater. $\text{Mg}(\text{OH})_2$ was probably formed by the reaction of Mg^{2+} ions with OH^- ions in the seawater.

In Figure 3, the measurement points are consistent with a theoretical curve [4] for flow rate reduction, according to the following equation

$$q = q_0 / (1 + 2 K_b t \cdot q_0 / q_i)^{3/2} + q_c, \quad (1)$$

where q is the flow rate, q_i is the flow rate at $t = 0$, q_c is the flow rate in the steady state ($q_0 = q_i - q_c$), K_b is the blocking coefficient, and t is time. For these results, K_b is 2.5 day⁻¹. For other measurements in this study, K_b ranged from 2.0 to 6.5 day⁻¹. The value of K_b is known to be about 1.0 day⁻¹ for experiments using a concrete specimen without steel reinforcement[4]. The present value of 2.5 day⁻¹ indicates a surprisingly fast blocking rate, given that a filter was used to remove foreign particles from the seawater and maintain the turbidity close to that of tap water. The only possible cause of such fast blocking or clogging that we can propose is the rich mineral and corrosion product content of the seawater.

In the case of a 0.26 mm-wide cleavage, or curve (b) in Figure 3, the leak rate fell much more slowly. Furthermore, the steady-state value was much larger, about one half of the initial value. This behavior was considered to be the result of blocking by low-solubility solids. Curve (c) corresponds to a flat, smooth-surfaced crack 0.90 mm in width, showing very

little change in flow rate. This is possibly because the fast flow through the wide, flat crack effectively prevented the deposit of suspended matter.

Figure 4 shows the dependence of flow rate on crack width. Here, the flow rate is the ratio of leakage to hydraulic gradient. Note that the vertical axis is a logarithmic scale. It is notable in this figure that water leaked through the flat cracks faster than through the cleavages with rough surfaces. It is also worth noting that the flow rate through flat cracks did not significantly decrease over time, while the flow rate through rough cleavages of 0.25 mm or less decreased nearly to zero. On the other hand, cleavages of 0.35 mm or more in width showed insignificant decreases. The broken curve in Figure 4 is consistent with a previous study [4], $q/i = 57.3w^3 \ell + 0.218w^2 \ell$, where w represents the width and ℓ represents the length of a crack. This curve closely corresponds to the initial flow rates in this study.

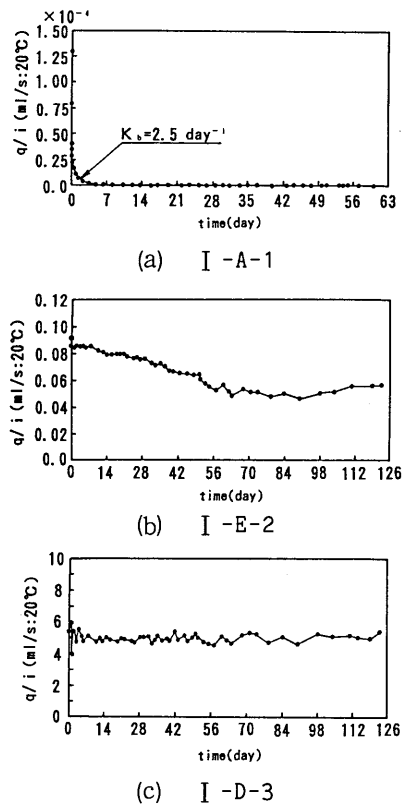


Fig. 3 Typical discharge [q/i] with time

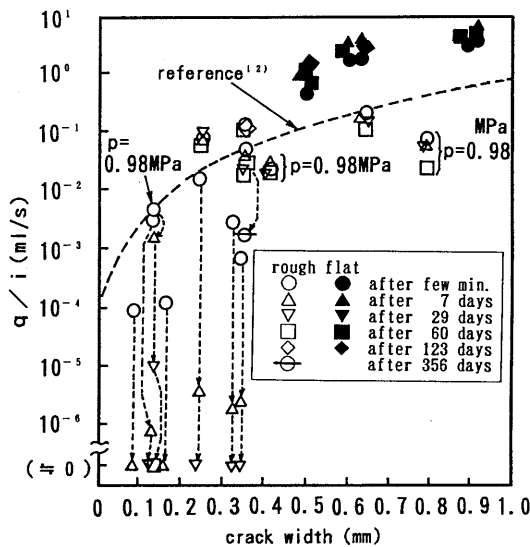


Fig. 4 Relationships between crack width and discharge

3.3 Corrosion of Steel Bars

(1) Visual Inspection

Figure 5 shows sketches of typical corroded steel bars taken from dismantled specimens. Photo 2 shows the external appearance of a steel bar at the end

of an experiment. Photo 3 shows the bottom surface two months after the start of the experiment. The findings from these sketches and photos are as follows: ① pitting corrosion prevailed because a localized area suffered severe corrosive action over a short period of time [5]; ② corrosion was worse under the action of circulating seawater than by stagnant seawater; ③ circulating seawater caused marked corrosion the surface of steel bars where they intersected cracks; ④ deformed bars corroded at the protrusion closest to the crack; ⑤ corrosion was more significant on the underside of a steel bar; ⑥ the greater the water pressure, the greater the area of corrosion; ⑦ two bars embedded in a specimen subjected to repeated wetting and drying corroded to a greater degree where the surface was exposed to ambient air during drying (i.e., on the upside of the upper bar and on the underside of the lower bar). When each specimen was dismantled, the corroded areas were found to be dark, indicating an oxygen deficiency. A few minutes after the specimen was dismantled, however, the area turned light green, then yellowish brown, indicating progressive oxidation in air.

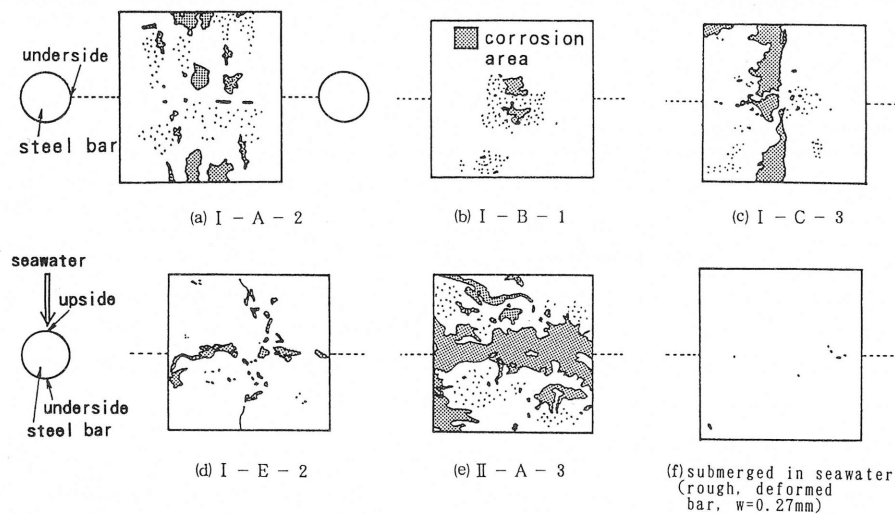


Fig. 5 Typical distribution of corrosion area in steel bars

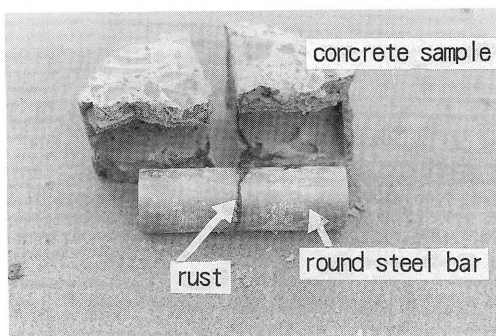


Photo 2 Test piece and steel bar for I - C - 1

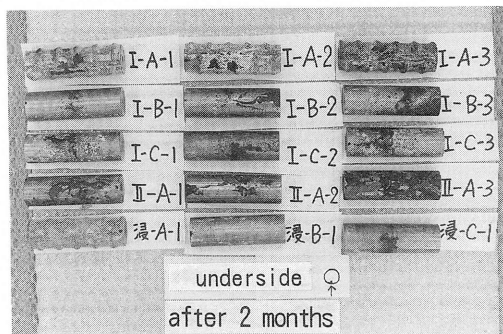


Photo 3 Rust distribution on underside of steel bars after two months of testing

(2) Corroded area of steel bars

Figure 6 shows the correlation between corrosion percentage and crack width. The percentage was small, ranging from 0.01% to 18.04%, because corrosion occurred only in the vicinity of the few cracks in each specimen. This figure indicates no significant correlation between amount of corrosion and crack width. Generally, circulating water led to more corrosion than stagnant water.

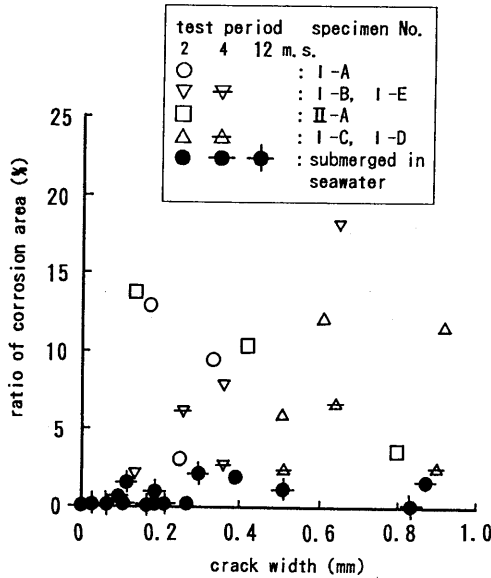


Fig. 6 Relationship between ratio of concrete area and crack width

(3) Steel bar corrosion rate

It was not possible to measure changes in the weight of the steel bars precisely enough to determine the corrosion rate. Instead, the pitting corrosion made it possible to determine the change in corrosion depth by measuring the bar's diameter. A point micrometer was used to measure the diameter at three different points along each bar: the center and at each end. Six measurements of each section at 30-degree intervals were made. After each experiment, six measurements of the bar's diameter at its center were also made. Taking the average values, the corrosion rate was evaluated using the following equation [5]:

$$\text{Corrosion rate} = \frac{\text{(Difference between pre- and post-experiment averaged diameter in mm)}}{2 \times (\text{number of experimental days}) / (365 \text{ days})} \quad (2)$$

(unit:mm/y)

Figure 7 shows the correlation between corrosion rate and crack width. The rate of corrosion resulting from circulating seawater ranged from 0.0 to 1.84×10^{-1} mm/y, while stagnant seawater caused corrosion rates ranging from 10^{-3} to 10^{-2} mm/y regardless of the crack width. The rate of corrosion when exposed to by circulating seawater increased as the crack width increased, except in the case of specimen I-D-3, which showed little

corrosion but featured extremely deep pits.

Figure 8 shows the correlation between corrosion rate and the total amount of seawater passing through a crack. Except in the case of the specimen described above, all measurement points indicated a weak dependence: an order of magnitude in the rise of the corrosion rate against an order of 10^6 .

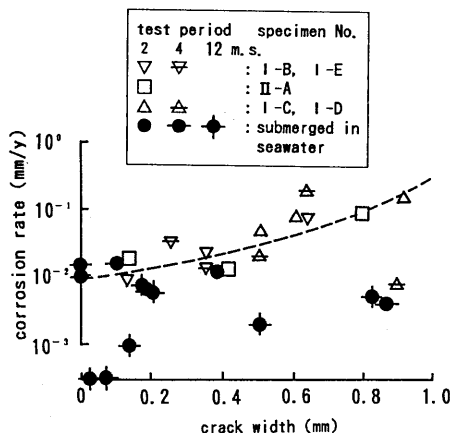


Fig. 7 Relationship between corrosion rate and crack width

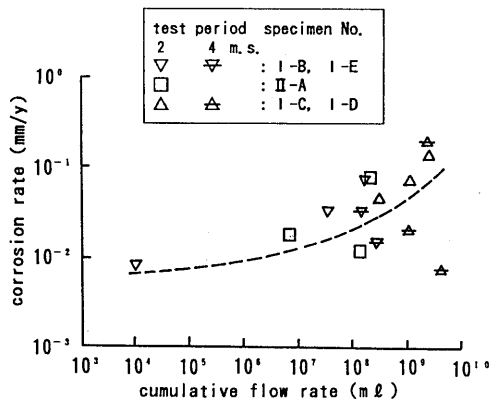


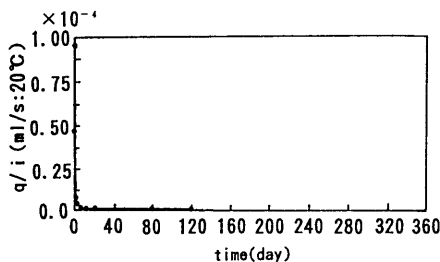
Fig. 8 Relationship between corrosion rate and cumulated discharge

3.4 Polarization Resistance

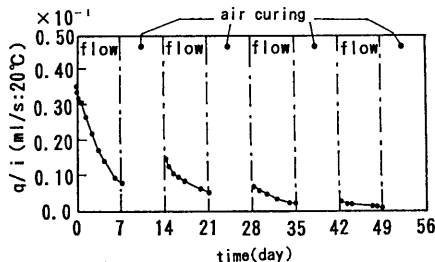
Generally, the external appearance of polarization-resistance specimens and other types of specimens used in the experiment described in Section 3.3 was similar. The two steel bars eroded in dissimilar ways. Table 3 shows the average rate of corrosion for the two bars during the measurement of polarization resistance. The two bars in the repeated wetting and drying experiment eroded much more than those in the circulation experiment and the immersion experiment.

Figure 9 shows typical changes in resistance (R_p and R_s) over time as compared with changes in the flow rate over time. In this figure, (a) and (b) represent measurements taken of specimens during 12 months of continuous exposure to circulating seawater, (c) shows immersion experiment measurements, and (d) and (e) show the repeated wetting and drying experiment measurements. In (a), the flow rate rapidly declines immediately after the experiment begins, and is near zero after seven days. In (b), R_p rapidly decreases during the first five days and increases slightly thereafter. Around the 120th day, R_p begins to increase more quickly and tends to decrease after approximately the 280th day. This flow rate behavior may indicate that corrosion occurs at a rapid rate during the initial stage, slows later, and increases again after approximately the 280th day. On the other hand, R_s in (b) tends to increase gradually over time. This is an indication that clogging probably occurred. From these results, we conclude that circulating water may have initially broken the oxide film on the steel bar and thus promoted corrosion. After this stage,

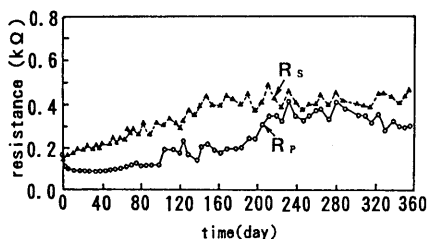
clogging of the crack causes a decrease in the flow rate and, therefore, of the corrosion rate. The increase after approximately the 280th day is presumably due to the high ambient temperature from late May through August. During this time, the seawater is warm enough to significantly promote corrosion.



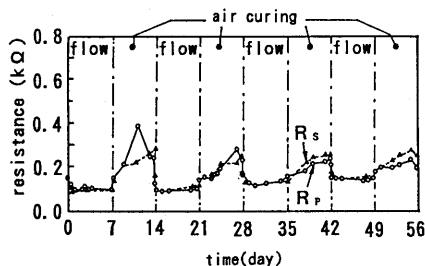
(a) I-F-1: discharge with time



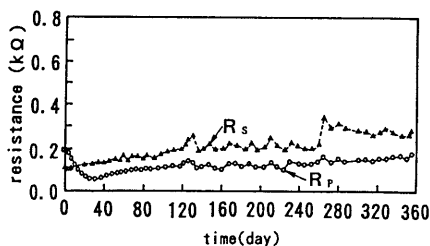
(d) II-B-3: discharge with time



(b) I-F-1: resistance with time



(e) II-B-3: resistance with time



(c) S-1: resistance with time

Fig. 9 Typical polarization resistance and discharge with time

In (c) of Figure 9, as in (b), R_p rapidly decreases initially and then tends to increase after the 40th day. R_s increases as a result of the continuous deposition of corrosion materials. In immersion experiments, as is generally known, oxide films may gradually break as stagnant seawater contained in cracks results in slow corrosion. After about 40 days, deposits of corrosion materials probably increase R_p and reduce the corrosion rate.

In the repeated wetting and drying experiment shown in (c) and (d) of Figure 9, both R_p and R_s are small while seawater is circulating, but increases rapidly during the drying period. Generally, these resistance values tend to increase over time. In the wetting cycle, corrosion proceeds in a fashion similar to corrosion during the continuous circulation of seawater. During the drying cycle, corrosion behavior depends on whether the seawater permeates the cracks and vaporizes.

As shown in Table 3, few measurements of polarization resistance R_p were made. Consequently their relationship to the corrosion rate is unclear.

As explained above, the AC impedance technique may be an effective method for qualitatively evaluating the tendency of cracks to cause clogging and blocking by corrosion products.

4. CONCLUSIONS

The corrosion of steel bars embedded in a cracked concrete block and submerged in artificial seawater was experimentally examined. The experiments simulated a hollow, undersea RC structure.

A summary of the results follows.

- (1) With crack 0.25 mm or less in width, seawater leakage stopped in the relatively short period of several months.
- (2) Low-solubility solids, comprising mainly CaCO_3 and $\text{Mg}(\text{OH})_2$, were the probable cause of this clogging.
- (3) Pitting corrosion was the most common type of corrosion observed in these experiments.
- (4) Corrosion occurred to a greater extent in circulating seawater than in stagnant seawater. It was also more severe in the repeated wetting and drying experiments than in the circulating seawater experiments.
- (5) Corrosion occurred to a much greater extent at crack intersections than at any other point on the steel bar's surface.
- (6) When the difference between the internal and external pressure in a structure was small, corrosion formed close to the crack intersection in insignificant amounts. As the difference between internal and external pressure increases, the area of corrosion increases as well. The ratio of corrosion area to total surface area of a steel bar was not directly dependent on crack width.
- (7) The greater the crack width and the total amount of seawater passing through the crack, the greater the erosion rate was. The rate depended more on crack width than on the total seawater flow.
- (8) The AC impedance technique appears to be useful for qualitatively monitoring the tendency of cracks to cause clogging and blocking by corrosion materials.
- (9) The polarization resistance tended to decrease initially and increase later.

To the limit of the authors' knowledge, this study is the first report on steel reinforcement bar corrosion for a situation in which seawater continually permeates the cracks. This report may be the starting point for corrosion prevention in actual situations similar to the conditions of this study. Unfortunately, the conditions studied were somewhat different from typical seawater environments[6]. The salinity and pH were nearly equivalent, but the seawater temperature was significantly higher, and the amount of dissolved oxygen was slightly less. Consequently the results of this study may differ from actual behavior in the natural environment. The

experimental conditions probably resulted in greater corrosion than would occur naturally.

ACKNOWLEDGMENTS

The authors are grateful to Dr. N.Otsuki of Tokyo Institute of Technology, Dr. S.Kobayashi and Dr.S.Katawaki of the Ministry of Construction, and Mr.T.Masuda of Nihon Doro Kodan for their helpful discussions. The authors are also grateful to Mr.N.Goto of Nippon Steel Corp. for his cooperation in measuring polarization resistance by the AC impedance method. The authors would further like to thank Mr.M.Shimomura and Mr.M.Hasegawa of Nihon Doro Kodan, and Mr.M.Kuroda of Shimizu Corporation, for their helpful suggestions during the experimental work.

REFERENCES

- [1] S.Fujita et al., "The design of a tunnel ventilation station constructed in an off shore manmade island," Structural Engineering, Vol.36A, pp.1319 ~1328, 1990.3 (in Japanese)
- [2] N.Goto et al., "Corrosion monitoring for reinforcing bars in concrete by AC impedance measurement," Proc. of JCI, Vol.12, No.1, pp.527 ~532, 1990 (in Japanese)
- [3] H.H.Uhig, "Corrosion and corrosion control," Sangyo Tosyo, pp.86~109, 1984 (in Japanese)
- [4] Y.Ito et al., "Experimental study on permeability of concrete cracks," Proc. of JCEA, 41, pp.217 ~220, 1987 (in Japanese)
- [5] JCI, "Guide for corrosion protection of off shore concrete structures," pp.103 ~106, 1988 (in Japanese)
- [6] National Astronomical Observatory, "Rika nenpyo," Maruzen, pp.694~697, 1989 (in Japanese)