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DURABILITY OF RC BEAMS WITH EPOXY-COATED BARS AND GALVANIZED BARS EXPOSED IN MARINE ENVIRONMENT FOR 15 YEARS

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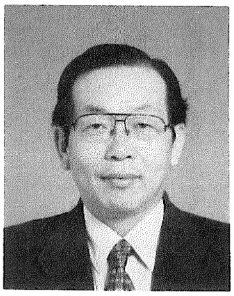


Tomio HOSHINO Taketo UOMOTO Kazusuke KOBAYASHI

This paper reports on the corrosion protection of epoxy-coated reinforcing bars as investigated through marine exposure tests on reinforced concrete beams over a period of 15 years. Some concrete beams using normal steel bars, which were made for comparison purposes, broke due to bar corrosion after 13 to 15 years of marine exposure. On the other hand, concrete beams using epoxy-coated bars had no discernable cracking due to corrosion and there was almost no corrosion on bars removed from the beams. It is ascertained from these results that epoxy-coated bars excel in long-term corrosion protection. Meanwhile, concrete beams made with galvanized bars for comparison, exhibited almost no sacrificial corrosion effect, and their behavior was little different from that of ordinary steel bars.

Key Words : epoxy-coated bars, galvanized bars, RC beams, marine exposure, steel corrosion, long-term durability

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Tomio Hoshino is a technical officer at the Institute of Industrial Science, University of Tokyo, Japan. His research interests concern the durability and corrosion mechanism of concrete structures. He is a member of the JSCE.

Taketo Uomoto is a professor at the Center for Collaborative Research, University of Tokyo. He received his D.Eng.degree from the University of Tokyo in 1981. His research interests are the constituents of concrete and composite structures. He is a fellow of the JSCE.

Kazusuke Kobayashi, an emeritus professor at the University of Tokyo, is presently a professor at Chiba Institute of Technology, Japan. He received his D.Eng.degree from the University of Tokyo in 1970. His research interests relate to the durability diagnosis of concrete and composite structures. He is a fellow of the JSCE.

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1. INTRODUCTION

Corrosion prevention of reinforcing steel bars is of extreme importance to the construction of durable concrete structures. The most common method of achieving this is to use low-permeability concrete with a low water-cement ratio and increase the thickness of the cover over reinforcing bars [1] .

When a structure is constructed in a severely corrosive environment, such as in marine environment or in a region where large amounts of deicing salt are used, the high concentration of chloride ions leads to ready corrosion of unprotected steel bars within a few years.

To deal with the problem, the JSCE (Japan Society of Civil Engineers) and the JCI (Japan Concrete Institute) have recommended the use of epoxy-coated bars in place of normal steel bars [2,3] . However, some researchers have asserted that galvanized bars are much more durable than epoxy-coated bars under such conditions.

To check the actual corrosion-resistant properties of these types of reinforcing bars, reinforced concrete beams with normal, epoxy-coated, and galvanized bars were exposed at a marine exposure site for a period of 15 years. This paper reports on the performance of these exposed beams together with the degree of corrosion measured on the bars.

2. OUTLINE OF EXPERIMENT

2.1 Mix Proportions and Materials Used

Ordinary Portland cement was used for the concrete. Fine and coarse aggregates were river sand (specific gravity: 2.61; absorption: 2.10%; F.M: 3.00) and crushed sandstone (specific gravity: 2.70; absorption: 0.63%; maximum size: 15mm), respectively.

The mix proportions of the concrete used for the beams were as shown in Table 1. The W/C ratio was kept at 0.60 and the sand-aggregate ratio at 47%. Assuming that in actual practice marine sand might be used without desalination, NaCl was added to the mixing water at a ratio of 0.3% by weight of fine aggregate to simulate this situation. To examine the effect of W/C ratio, a concrete mix of W/C ratio 0.50 (s/a: 45.5%) was also used in some of the beams tested.

Table 1 Concrete mix Proportions

W/C	s/a	Unit wt. (kg/m^3)			
	%	W	C	S	G
0.50	45.5	196	392	808	997
0.60	47.0	196	327	859	999

Three types of reinforcing steel bars were used: normal, epoxy-coated, and galvanized. The normal bars were 10-mm diameter deformed bars meeting the requirements of JIS (Japanese Industrial Standard) G3112.

The epoxy-coated bars used satisfy the relevant JSCE standard specification [4] produced in Japan. The bars were coated with epoxy resin powder by electrostatic spraying. The base material of the coating material was epoxy resin of bisphenol epichlorohydrin type and the curing agent was an acid anhydride. The steel bars were the same 10-mm diameter deformed bars as described above, but they were blasted to near-white metal condition before coating. The average thickness of the coating was 196μm, with a standard deviation of 24μm. The number of pin holes measured by a holiday detector at 1 kV in accordance with the standard JSCE test method [5] was 3-4 per meter.

The galvanized steel bars were produced in Japan to meet JSCE standard specification [6] requirements. Galvanizing was done by the hot-dip method. The target coating thickness was $150\mu m$ and the amount of zinc adhering to the bars was 1,060-1,360g/m^2.

2.2 Beam Specimens and Exposure Site

As shown in Table 2, six types of $10\times10\times110$-cm rectangular beam specimens were prepared. Four specimens of each were made. The beams were cured in a moist environment($60\pm3\%$ R.H.) for 28 days at 20 ± 3℃.

Before exposure, the beams were arranged in pairs as shown in Fig. 1, with stainless steel bolts tightened at the ends such that flexural cracks at the concrete surface would range in width from 0.2 to 0.3mm.

Table 2 Properties of Reinforced Concrete Beams

Kind of bars	Designation	W/C	Chloride	Cover
Normal steel	N50−2	0.50	Contained	2
Normal steel	N60SO−2	0.60	None	2
Normal steel	N60−2	0.60	Contained	2
Normal steel	N60−3	0.60	Contained	3
Galvanized	Z60−2	0.60	Contained	2
Epoxy-coated	E60−2	0.60	Contained	2

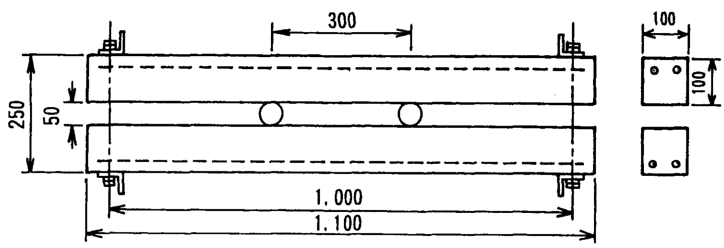


Fig. 1 Assembly of Exposed Beams (Unit: mm)

The exposure site is located on the coast of the Izu peninsula in Shizuoka Prefecture, facing the Pacific ocean as shown in Fig.2. Sea water splashes the site continuously, washing the specimens throughout the year. Exposure of the test specimens began in 1979 and the results reported here were obtained in 1995. The average temperature at the site was 16℃ and the average amount of NaCl carried by the sea breeze aside from that in the sea water itself was 2.93mg/day/100cm^2. Inspections of the beams were carried out every six or twelve months.

2.3 Inspection and Testing

The following inspections and tests were carried out after exposure of the concrete beams:

1) inspection of crack distribution and crack width at the concrete surface,
2) half-cell potential measurements on the surface of concrete beam,
3) load-bearing behavior of exposed beams and reinforcing steel removed from beams,
4) tensile loading test of corroded steel bars,
5) measurement of chloride ion profile inside concrete,
6) observation by EPMA and chemical analysis,

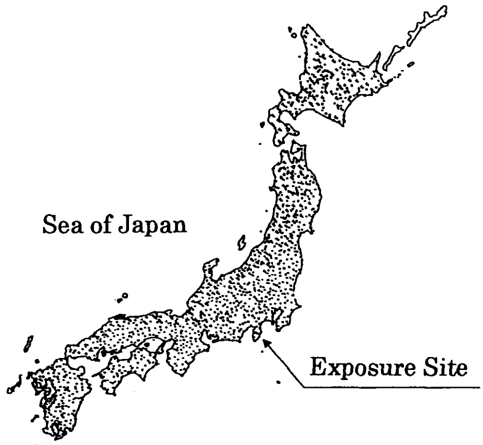


Fig.2 Location of Exposure Site

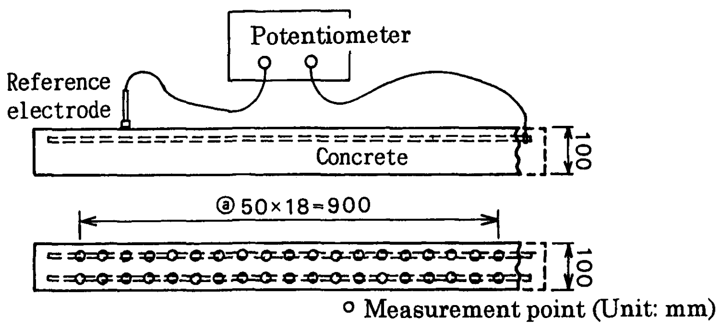


Fig.3 Half-Cell Potential Measuring Setup

Half-cell potential measurements were performed using a reference electrode of Ag/AgCl as shown in Fig.3.

Flexural tests of the exposed beams were performed, as shown in Fig.4. The span was 90cm and the distance between the loading points was 20cm. Both load and deflection at the center were measured. After these tests, the reinforcing bars were removed from the specimens and tensile strength tests were carried out on the bars.

The usual attachment-type gauges could not be used to measure tensile strains of corroded bars during tensile strength tests since the specimens had imperfect cross sections due to corrosion. Consequently, special gauges (measuring range : 5cm ; capacity : 5mm ; sensitivity : 1,244$\times 10^{-6}$/mm) capable of gripping the two ends of a bar were used.

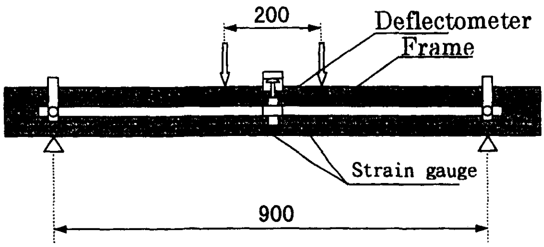


Fig.4 Flexural Loading Test Method (Unit: mm)

The chloride concentration in the concrete was measured by taking a core sample, 30mm in diameter, cutting the sample from the top into 1-cm slices, and testing using the methods defined in JCI-SC4 and JCI-SC5 [7].

For observations by EPMA (Electron Probe Micro-Analyzer), samples about 10-mm thick including reinforcing bars were sliced from the beams. The elements targeted for analysis by EPMA were carbon (C), the main component of the epoxy resin coating, chlorine (Cl), the main element in sea water, and calcium (Ca), the main element of the cement in the concrete.

As for chemical analysis of the coated epoxy, the coating bars was removed from concrete beams using a solvent, with examination and measurement by DSC (Differential Scanning Calorimeter).

3. TEST RESULTS AND DISCUSSION

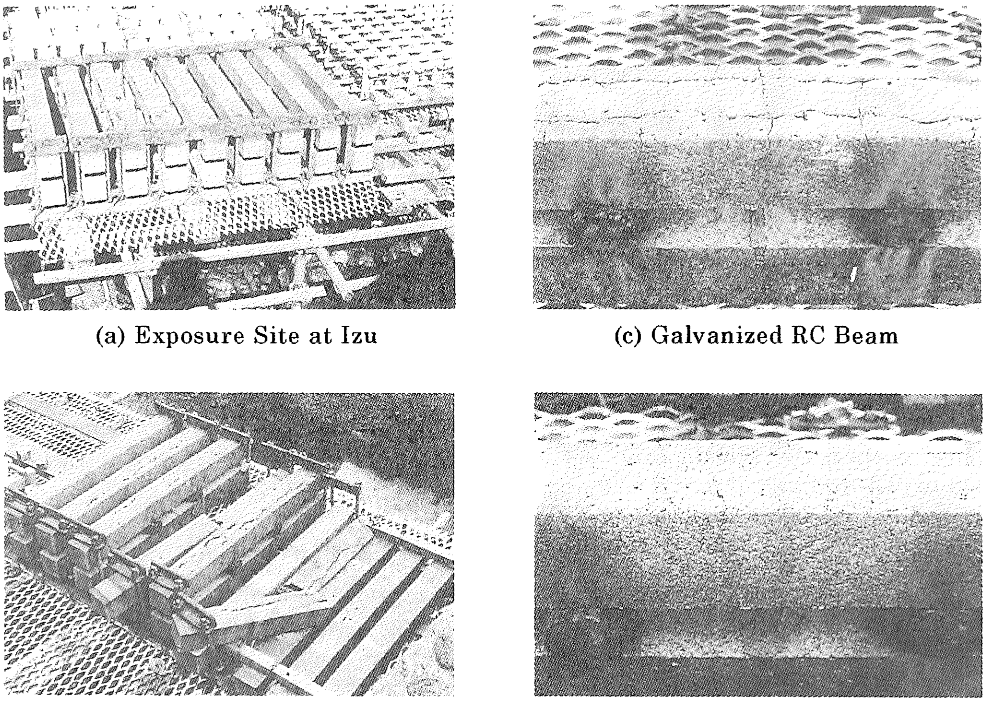
3.1 Cracks and Appearance of Specimens

The appearance of the exposed specimens is illustrated in Fig.5(a-d) just before removal from the exposure site. As shown in figure 5(b), two beams with normal steel bars (W/C:0.50 and 0.60) had collapsed at their centers prior to removal. These beams had not failed at the time of the previous inspection as shown in Fig.5(a), indicating that they had collapsed within the last six months of exposure.

As shown in Fig.5(b-c), longitudinal cracks were observed in all beams except those with epoxy-coated bars. In the case of beams with normal steel bars, all showed longitudinal cracks just above the bars. Crack widths ranged from 0.2 to 0.5mm in beams with a W/C ratio of 0.60, but were smaller in beams with a W/C ratio of 0.50. With beams using galvanized bars, although they had collapsed as in the case of normal steel bars, longitudinal cracks were observed along the bars in all of the beams. Crack widths ranged between 0.2mm and 2mm. In the case of beams with epoxy-coated bars, no longitudinal cracks were observed on the surface although there were flexural cracks that had been induced before exposure.

Figure 6 shows examples of cracks observed on the tensile surfaces of the beams and the appearance of the reinforcing bars after the concrete cover was removed. It can be readily seen that large amounts of corrosion had occurred in beams with a W/C ratio of 0.60, except where epoxy-coated bars were used. This corrosion was the main cause of the observed longitudinal cracks. With epoxy-coated bars, a fair amount of corrosion was observable close to the flexural cracks. The coating at other portions was sound and showed no sign of corrosion.

These results indicate that coating with epoxy resin is a highly effective way to protect reinforcing bars from corrosion as compared with galvanizing.



(a) Exposure Site at Izu

(c) Galvanized RC Beam

(b) RC Beams at Exposure Site

(d) Epoxy-Coated RC Beam

Fig.5 RC Beams After 15 Years of Exposure (b-d)

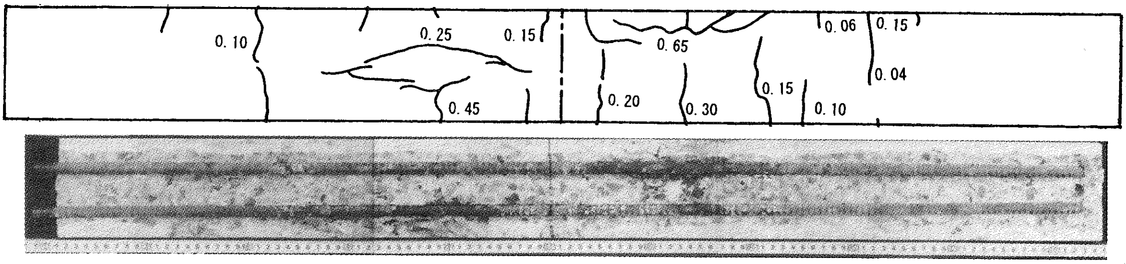
3.2 Half-cell Potential

Examples of half-cell potentials measured for individual beams are shown in Fig.7. It is obvious that although half-cell potentials ranged between -300mV and -500mV for all beams, the half-cell potential of beams with epoxy-coated bars (shown in Fig.7(d)) was almost constant at -400mV over the entire length of the bar. The relation between corroded state and half-cell potential, other than for the epoxy-coated bars shown in Fig.7(a-c), is notable in that the whole bar is corroded. In contrast, the degree of corrosion in all epoxy-coated bars was small and only a small amount of loose rust was noticeable.

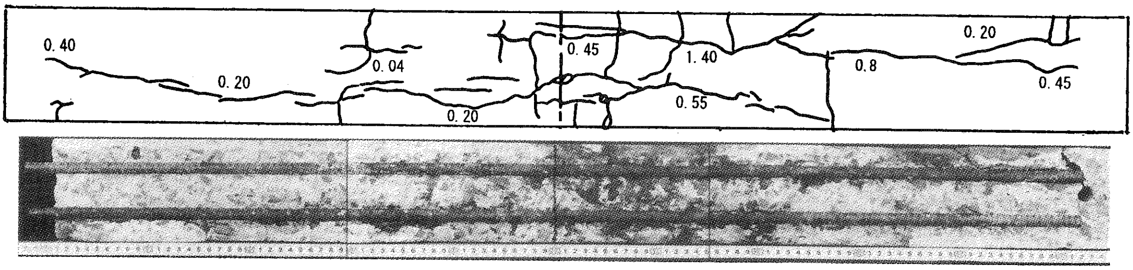
It is considered that this means the half-cell potentials of epoxy-coated bars shown in Fig.7(d) had picked up the corroded portions over a wide area even though that corrosion was slight. On the other hand, looking at beams with other types of steel bar, the middle portions where corrosion was severe, the half-cell potentials were 50-100mV less negative than that of other portions. This differs from the findings of past research reports, but it indicates that when corrosion progresses to the stage where reinforcing bars rupture, the half-cell potential and corroded state no longer correlate due to the influence of loosening of cover concrete and the presence of corrosion products of reinforcing steel.

3.3 Flexural Behavior of Beams

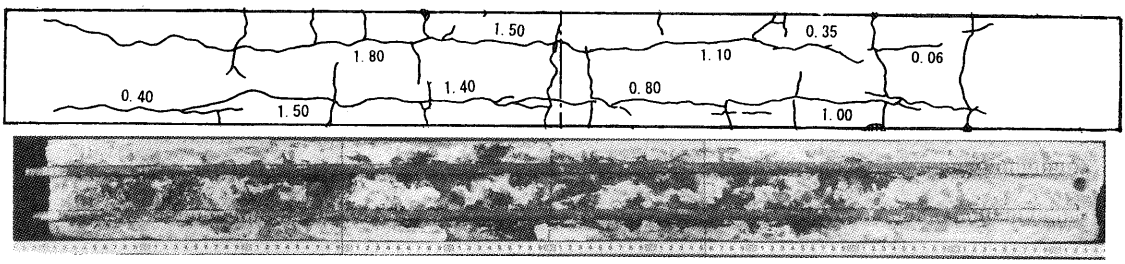
Load-deflection curves obtained for the different types of beams up to a deflection of 2 mm are shown in Fig.8. These results show that beams using epoxy-coated bars had the highest load-carrying capacity. Beams with normal steel bars had the lowest capacity, at 0.5 (W/C: 0.6; cover: 3cm) to 0.6 (W/C: 0.6; cover: 2cm) that of epoxy-coated bars. In the case of beams with galvanized bars, the ratio was about 0.75.



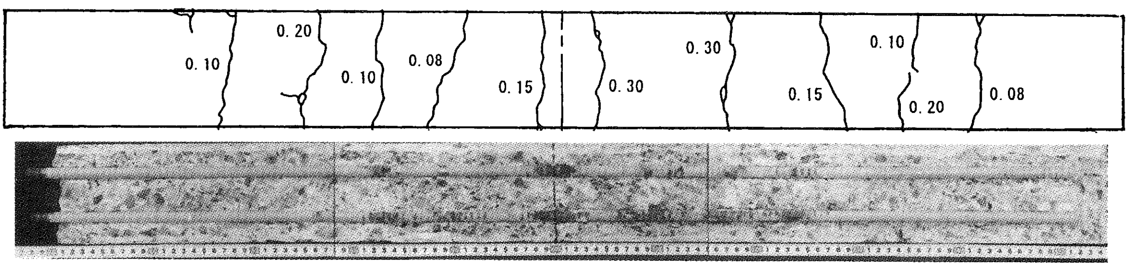
(a) Normal Steel RC Beam (N50−2)



(b) Normal Steel RC Beam (N60−2)



(c) Galvanized Steel RC Beam (Z60−2)



(d) Epoxy-Coated Steel RC Beam (E60−2)

Fig,6 Cracking in RC Beams and Locations of Corrosion on Bars
(15 Years of Marine Exposure, Crack Width in mm)

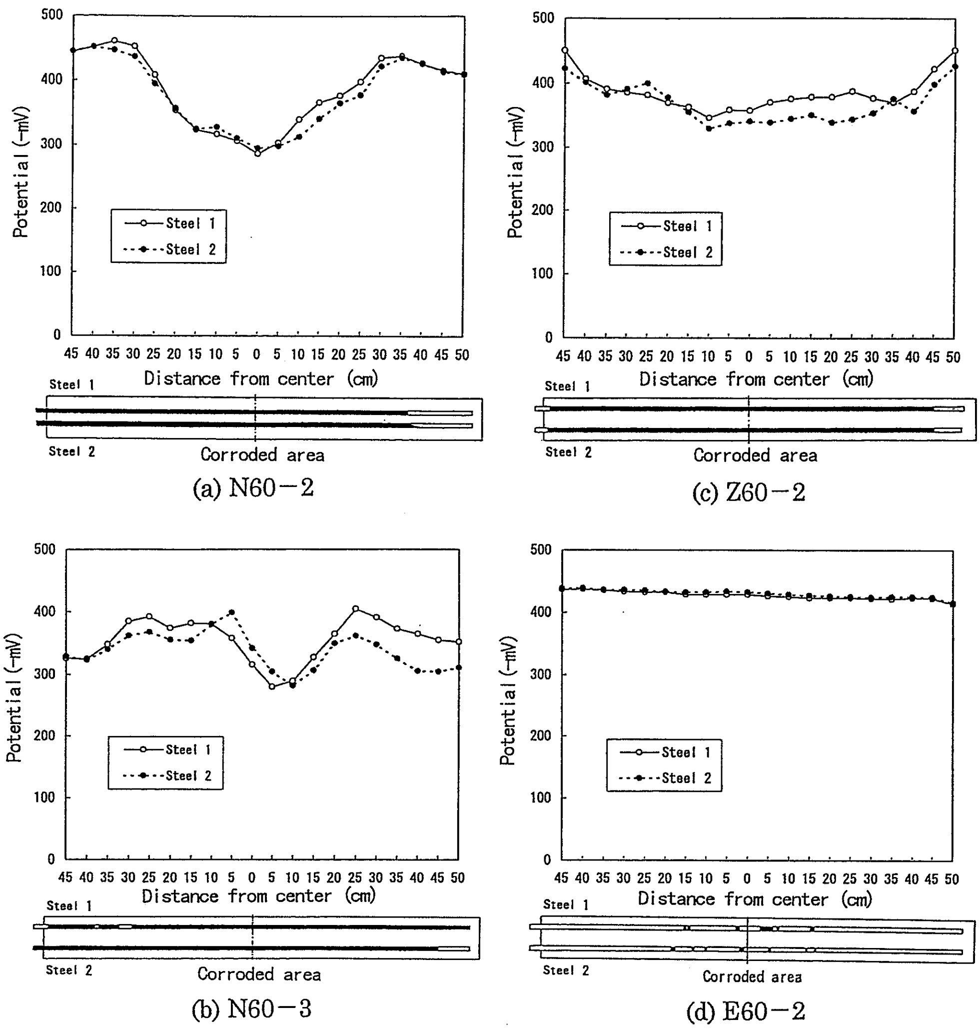


Fig.7 Potential and Corroded Portions of Bars in RC Beams

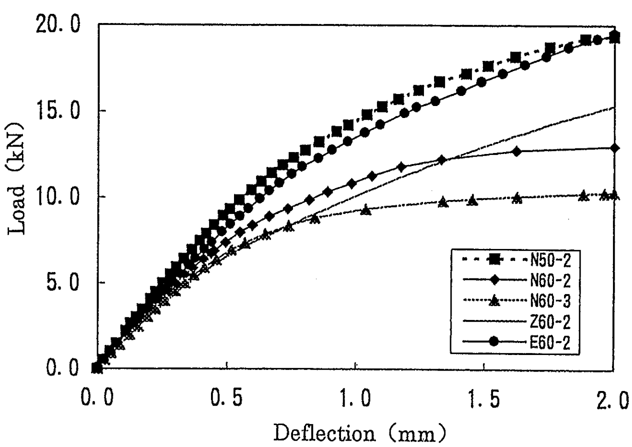


Fig.8 Load-Deflection Curves for Exposed RC Beams

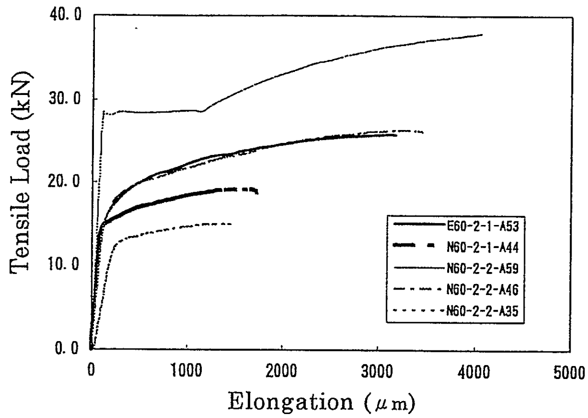


Fig.9 Tensile Load-Elongation Curves for Steel Bars
(Normal Steel Bars: N60－２)

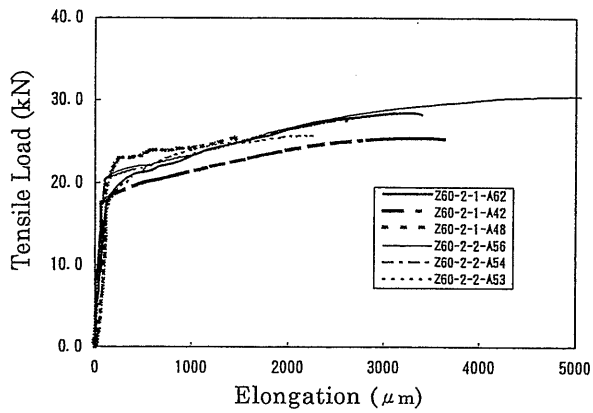


Fig.10 Tensile Load-Elongation Curves for Steel Bars
(Galvanized Bars: Z60－２)

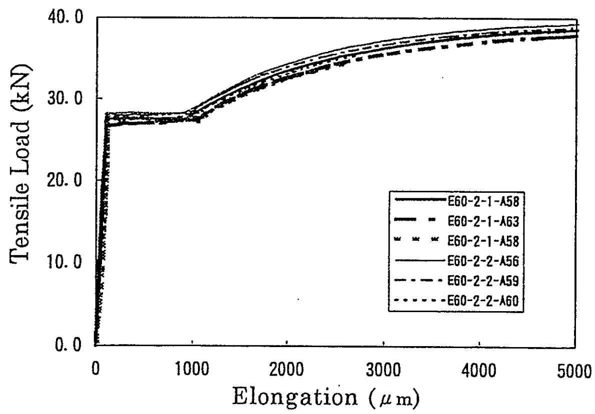
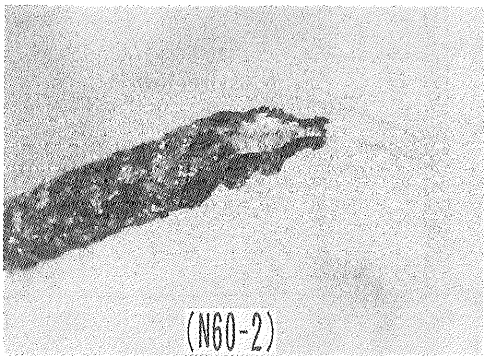
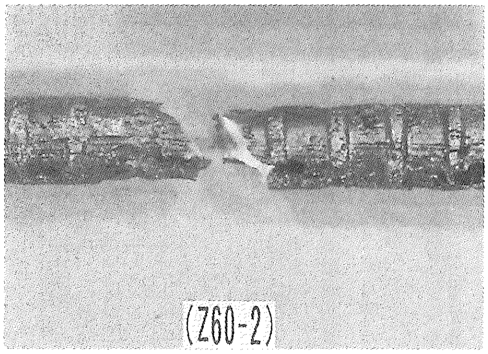


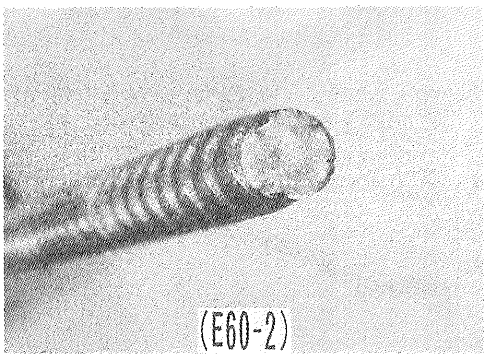
Fig.11 Tensile Load-Elongation Curves for Steel Bars
(Epoxy-Coated Bars: E60－２)



(a) Normal Steel Bar



(b) Galvanized Steel Bar



(c) Epoxy-Coated Bar

Fig.12 Rupture Planes of Bars Removed from Beams

The load-deformation curves of epoxy-coated bars and normal steel bars removed from exposed beams are different, as shown in Figs.9 and 11. The tension test specimens for which results are given in these figures were specimens cut from 2 to 4 extremely corroded locations and sound sections (where no rust was visible). Suffixes starting with "A" in the legends of these figures indicate cross-sectional areas (mm^2) obtained from the section where rupture occurred in tension tests.

Looking at the relations between tensile load and elongation for normal steel bars, as shown in Fig.9, distinct yield points are visible for specimens cut from non-corroded locations. But when corrosion had progressed and the cross section was reduced, yield points were indistinct and elongations became less than 3,500 μm.

In the case of galvanized bars, as shown in Fig.10, reduction in the cross-sectional area of bars due to corrosion was less than with normal steel bars, but there were no distinct yield points for any of the bars. On the other hand, in the case of epoxy-coated bars, as shown in Fig.11, although some had a slight amount of loose rust, this did not affect tensile strength or elongation.

Examples of rupture planes of the steel bars after tension tests are shown in Fig,12. In the case of the normal steel bars in Fig.12(a), it can be seen that corrosion had progressed considerably. As for the galvanized bar shown in Fig.12(b), no large cross-sectional loss was seen, but cracking had occurred as a result of corrosion. The behavior of coated bars with small amounts of corrosion was almost equivalent to that of new steel bars.

3.4 Chloride Distribution in Concrete

Figure 13 shows the distribution of chlorides in concrete as measured from the beam top. Significant amounts of chlorides (more than 0.4 wt. % in term of NaCl) were observed at all depths. Compared with the beam made from concrete with a W/C ratio of 0.5, all the beams cast with concrete of W/C ratio 0.60 had similar trends. Concentration of chlorides was high at the top of a beam and low at the bottom.

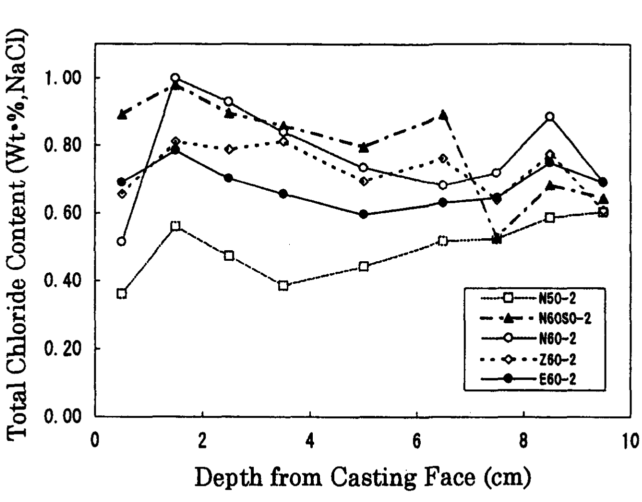
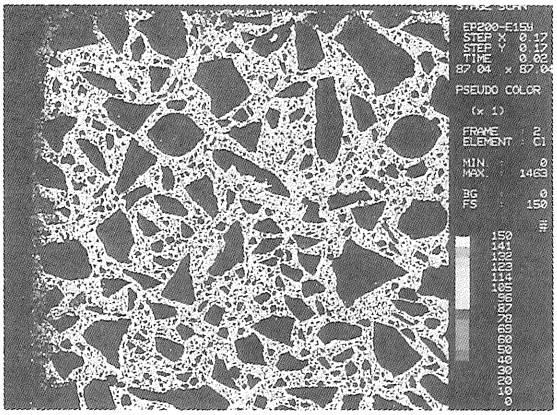


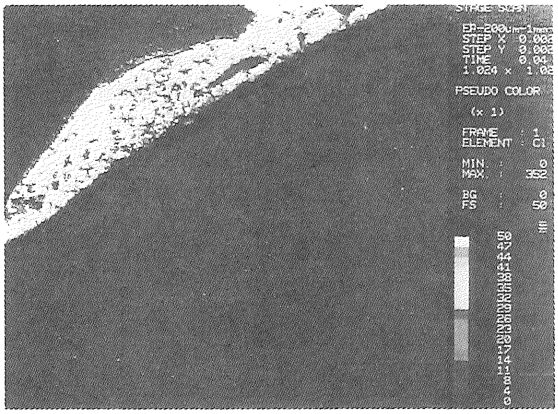
Fig.13 Chloride Distribution in Concrete (15 Years of Exposure)

3.5 Observation by Electron Probe Micro-Analyzer

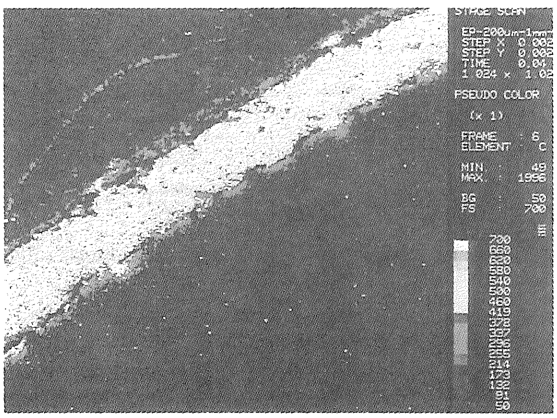
Observation by EPMA is an effective means of diagnosing deterioration of concrete, and Fig.14 shows examples of area analysis results obtained by EPMA. White portions of the figure are high in concentration of the elements analyzed. Figure 14(a) shows the distribution of chlorine through a cross section of a concrete beam in which epoxy-coated bars were embedded. It can be seen that chlorine had penetrated to the center of the beam. This corresponds well with the chloride distribution in Fig.13 obtained by the previously mentioned chemical analysis. An area of approximately 1 cm around the coated bar was enlarged and analyzed by EPMA; the results



(a) Distribution of Chloride in Concrete



(b) Chloride Distribution near Epoxy-Coated Bar



(c) Carbon Distribution near Epoxy-Coated Bar

Fig. 14 Results of Analysis by EPMA (E60 - 2) are given in (b) and (c) of Fig.14, where (b) shows the analysis for chlorine, and (c) that of chlorine, the main element of the epoxy resin coating. It may be seen that attack by chloride has been effectively blocked. It can also be seen that the carbon in (c) is in continuous form even after 15 years of exposure. The corrosion-resistant effect of epoxy-coated bars in concrete beams is thus clearly shown through EPMA observations.

3.6 Chemical Analysis

The soundness of the epoxy resin coating was examined by bringing a solvent into contact with it; this is one method of testing the deterioration of such coatings on reinforcing bars. Figure 15 gives the results of DSC (Differential Scanning Calorimeter) analysis performed to investigate the deterioration properties of coatings on epoxy-coated reinforcing bars.

The broken line in the figure represents analysis of the coating of an epoxy-coated bar currently in production; a softening point accompanying temperature rise, noise, etc. is hardly noticeable. In comparison, the coating used in the exposure tests shows a softening point and noise to some extent.

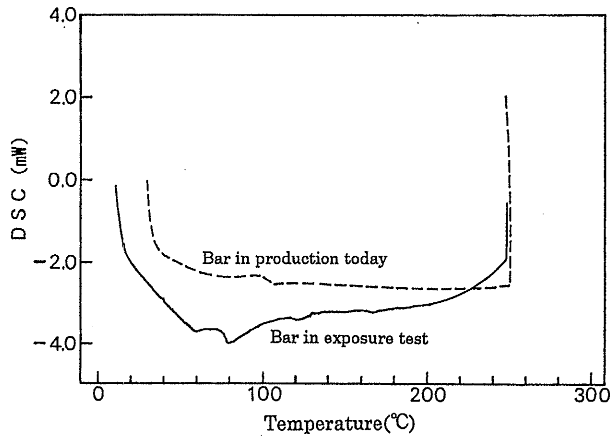


Fig.15 Results of DSC Measurements on Coated Epoxy

This may be considered due to time-dependent deterioration of the coating during the exposure period, but it should also be considered that the product was less stable compared with epoxy-coated reinforcing bars now being made. Some amount of bar corrosion was recognized where cracking had been made to occur at the beginning in the epoxy-coated bar used in the current marine exposure tests, and it is thought that such defects had an influence.

4.CONCLUSION

Marine exposure tests over a period of 15 years were conducted on reinforced concrete beams using epoxy-coated bars as a part of an investigation to establish a corrosion protection method for reinforced concrete structures. The following conclusions were reached:

1) The epoxy-coated reinforcing bars used in the test were products made before JSCE standards had been established and do not necessarily meet those standards. However, their corrosion behavior and physical properties were superior to those of both normal steel bars and galvanized bars, and significant corrosion-prevention effects were seen in long-term marine exposure.

2) Many reinforced beams using normal steel bars collapsed due to bar corrosion at 13 to 15 years of marine exposure. The corrosion behavior of hot-dip galvanized bars in reinforced concrete beams exposed at the same time was not much different from that of normal steel bars, and it was confirmed that the mechanism of sacrificial corrosion protection did not function in a marine environment.

3) It was ascertained that epoxy-coated reinforcing bars are the only suitable means to protect reinforced concrete structures against corrosion in a severe corrosion environment such as a marine splash zone or a region where deicing salt is heavily used.

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