CORROSION OF STEEL BARS IN CHLORIDE-CONTAMINATED CONCRETE MEMBER PATCHED WITH SELF-COMPACTING CONCRETE

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The progress of steel corrosion in model specimens of chloride-contaminated beams patched with self-compacting concrete is investigated in this study.

Self-compacting concrete is superior to normal concrete of the same compressive strength in protecting steel bars from chloride-induced corrosion, and recurrence of deterioration is impeded in self-compacting concrete parts. On the other hand, macro-cell corrosion is more severe in chloride-contaminated parts adjoining a self-compacting concrete patch.

Keywords : corrosion, chloride, repair, half-cell potential, polarization resistance, macro-cell corrosion, self-compacting concrete

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1. INTRODUCTION

Despite the inherent durability of concrete, the premature deterioration of concrete structures has caused many serious problems recently. Corrosion of the reinforcing steel is typically the cause of such deterioration. Steel bar corrosion can be visually detected when the cover concrete cracks, but the presence of cracks is a sign that corrosion has progressed to a certain level, and it also leads to a rapid increase in corrosion rate. Moreover, at this stage, it is more difficult to repair the structure as corrosion progresses. Consequently, it is very important to monitor the state of reinforcing steel corrosion and to treat it properly at an early stage. On the other hand, repairs to a deteriorated structure without a correct understanding of the corrosion mechanism may accelerate the deterioration process because of macro-cell corrosion.

In this study, the macro-cell corrosion that occurs in steel bars due to differences in chloride concentration in the cover concrete was investigated using electrochemical methods [1]~[5], simulating a case in which a concrete structure suffering from chloride-induced corrosion is repaired by patching with self-compacting concrete.

Self-compacting concrete is a material designed to have superior self-compactability, and it is able to fill all corners of formwork without compacting vibration. Thus, it is considered advantageous for repair work, since this often requires injection of concrete into confined space.

Another characteristic of self-compacting concrete is its superior resistance to the penetration of chloride ions, carbon dioxide, water, and so forth [6][7]. However, because of these characteristics, it may lead to variable corrosion of the reinforcing steel.

2. EXPERIMENTAL PROCEDURE

2.1 Materials and Mixtures

Table 1 shows the mix proportions used for experimental specimens and Table 2 the materials employed in these mixtures. Three types of ordinary concrete were prepared : chloride ions were added (1.5% and 3.0% per unit mass of water) to two mixtures of ordinary concrete, N15 and N30, to simulate chloride-induced corrosion, while no

	W/C	W/(C+Lp)	s/a	Unit mass (kg/m³)						Water- reducing agent	Air- entraining	Compressive strength
	(%)	(%)	(%)	w	С	Lp	S	G	NaCl	(C+Lp)×%	(C+Lp)×%	(N/mm ²)
NN			50.0	183	305		867	891	0			32.4
N15	60	60	49.9	183	305	0	864	892	4.582	0.25*	0.0053	30.1
N30			49.7	184	306		861	894	9.181			29.2
SL	60	32.4	50.0	170	283	242	780	800	0	2.1**	0.01	34.9
SH	45	33.1	50.1	174	387	138	783	800	U	2.2**	0.01	49.0

 Table 1
 Mix proportions

* Water-reducing agent

** High-range water-reducing agent

Cement	Ordinary Portland cement ; Specific gravity : 3.15, Blane fineness : 3260cm ² /g				
Limestone powder	CaCO ₃ >95% ; Specific gravity : 2.73, Blane fineness : 6770cm ² /g				
Fine aggregate	River sand ; Specific gravity : 2.57, Water absorption : 1.80%, Fineness modulus : 2.63				
Coarse aggregate	Crushed stone ; Specific gravity : 2.64, Maximum size : 15mm, Fineness modulus : 6.18				
Water-reducing agent	Lignosulfonic acid				
High-range water reducing agent	Polycarboxylic acid				
Air-entraining agent	Rosin-based anionic surfactant				

Table 2 Properties of materials

chloride ions were mixed in another mixture, NN. The concentration of chloride ions in mixture N15 slightly exceeds the 1.2~2.5kg/m³ threshold for corrosion of reinforcing steel as reported by some researchers [8][9]. These chloride ions were added by blending sodium chloride into the concrete during mixing, and the same mass of sand was removed from the specified mix proportions.

Two types of powder-type self-compacting concretes using limestone powder were prepared, one with the same water-binder ratio as for ordinary concrete so as to obtain normal strength, mixture SL, and one with a lower waterbinder ratio so as to obtain higher strength, mixture SH.

2.2 Specimens

Two types of beams were prepared for this study.

The vertical-jointed specimen shown in Fig. 1 had vertical joints to simulate an uneven chloride ion distribution in a case wherein the bottom surface of a beam is repaired by patching. Two deformed reinforcing steel bars 10mm in diameter and 700mm in length with mill scale were embedded in the specimens with 20mm of concrete cover (twice the bar diameter). Electrical cables rated at 100 volts and with a resistance of 14Ω per a meter were soldered to one end of each steel bar after exposing the steel by grinding off the mill scale. These were used for measuring halfcell potentials and polarization resistance. The exposed ends of the steel bars were then wrapped with a self-bonding insulating tape and further covered with epoxy resin to prevent the ingress of water, which causes steel corrosion.

Mixtures NN, SL, and SH were placed as the central part of the vertical-jointed specimen, and mixtures NN, N15, and N30 were placed to form the left and right parts of the specimen. The central part was placed on the first day. Water was sprayed on the joint surfaces of the central part, after which the left and right parts were

	L	С	R			
N15-NN-N15	NU 5		N15	Benaired u		
N15-NN-N30	NI3	NN	N20	normal co		
N30-NN-N30	N30		1130			
NN-SL-N15	NN	SL	N15]		
N15-SL-N15	N15		INTS	Repaired w		
NN-SL-N30	NN			self-comp of norm		
N15-SL-N30	N15		N30			
N30-SL-N30	N30			_}		
NN-SH-N15	NN		N15	ή		
N15-SH-N15	N15	1.1		Repaired w		
NN-SH-N30	NN	SH		self-com		
N15-SH-N30	N15		N30	of high s		
N30-SH-N30	N30			1		
NN	NN			7		
NN-NN-NN	NN	NN	NN			
N15		N15				
N30		N30		For investig		
N30-N30-N30	N30-N30-N30 N30		N30	influence		
SL	SL					
SL-SL-SL	SL	SL	SL			
SH	SH					

Table 3 Vertical-jointed specimens

vith NN, oncrete

vith SL, pacting concrete al strength

vith SH, pacting concrete strength

gation of of joints



Fig. 1 Vertical-jointed specimen (unit : mm)

jointed thereto on the next day. The specimen was demolded on the third day.

Table 3 shows the combination of mixtures used in each type of vertical-jointed specimens. Two beams were prepared for each discrete type of specimen.

In order to investigate the effects of the actual joints, into which chloride ions may penetrate, specimens of each type of concrete alone were prepared. Further, specimens with two joints were prepared using the same concrete throughout, with the left and right parts placed on the second day.

The horizontal-jointed specimen shown in Fig. 2 has a horizontal joint for the investigation of macro-cell corrosion and micro-cell corrosion. Four deformed reinforcing steel bars 10mm in diameter and 300mm in length with mill scale were embedded in the specimens with a concrete cover of thickness 20mm. Cables were attached as with the vertical-jointed specimens. Mixtures NN, SL, and SH were placed as the bottom layer of the horizontal-jointed specimen on the first day. Water was sprayed on the joint surface, after which mixtures NN, N15, and N30 were placed as the top layer of the specimen on the next day. The specimen was demolded on the third day.

Table 4 shows the combination of mixtures used in each type of horizontal-jointed specimen. Two beams were prepared for each discrete type of specimen.

One-piece specimens were also prepared as with the vertical-jointed specimens.

Both vertical-jointed specimens and horizontal-jointed specimens were left in a laboratory at ambient temperature after demolding, and 5 percent chloride sodium solution was sprayed on them once a day.

After demolding, all specimens were held on wood spacers with the placement surface upwards, while their bottom surfaces were kept wet.

Joint surfaces were not treated in the usual way, such as with chipping and the like. This is because self-compacting concrete is known to have superior bonding strength [10], and because patch repairs are usually performed in locations where such treatment is difficult to implement. Also, since concrete beams or slabs are often patched from the underside in actual practice, the laitance on the surface of patched concrete cannot usually be removed. Therefore, the only treatment given to joint surfaces was to spray them with water.

The compressive strength values of the concrete at the age of 28 days, as given in Table 1, were obtained from specimens with a diameter of 100mm and a height of 200mm. These were cured in the same way as the vertical-jointed specimens and the horizontal-jointed specimens.

2.3 Test procedures

Fig. 1 shows the halfcell potential measuring points for the steel bars in vertical-jointed specimens. Measurements were made using a reference electrode of saturated chloride silver through the 20mm concrete cover at intervals of 100mm and at joints.

The polarization resistance of the steel bars was measured by a double rectangular pulse method with a current intensity of 10μ A~1mA and at frequencies of 0.1Hz and 800Hz. A copper plate measuring 100mm in width and



Fig. 2 Horizontal-jointed specimen (unit : mm)

 Table 4 Horizontal-jointed specimens



800mm in length was placed in close contact with the concrete cover and used as the counter electrode. The reference electrode, consisting of saturated chloride silver, was attached to the side of the specimen of the midpoint of the steel bars in the longitudinal direction.

These measurements were made at the age of 3, 5, 7, and 14 days, and thereafter every one or two weeks.

The polarization resistance of the steel bars was also measured using an AC impedance method with a current intensity of $1\sim10mV_{p-p}$ and a frequency of $10mHz\sim10Hz$ at the points shown in Fig. 1 through the 20mm concrete cover at the age of 160 days. The counter electrode used for the AC impedance method was a double-disk type [11] consisting of a main center disk 40mm in diameter and an enclosing guard disk 108mm in diameter, as shown in Fig. 3. Polarization resistance in this case was calculated only from the current between the steel bar and the main center counter electrode.

The four cables connected to the steel bars in the horizontal-jointed specimens were bound into a single bundle to allow current to flow among the steel bars.



Fig. 3 Counter electrode for AC impedance method (unit : mm)

The halfcell potential of steel bars in the horizontal-jointed specimens was measured using a reference electrode of saturated chloride silver through the 20mm concrete cover. Furthermore, polarization resistance was measured by the double rectangular pulse method as with the vertical-jointed specimens, using a copper plate 100mm in width and 400mm in length as a counter electrode on the cover surface. At the age of 160 days, the polarization resistance of the steel bars was measured by the AC impedance method already described. The above measurements were made after the cables were separated.

Further, the macro-cell corrosion current flowing from the bottom bars to the top bars was measured with a coulomb meter after 28 days age.

One of each discrete type of vertical- and horizontal-jointed specimen was broken up for removal of the steel bars. The state of steel corrosion of each steel bar was sketched and the corroded area on the surface was calculated. The corrosion loss of these steel bars was estimated according to a JCI method [12].

The total chloride ion content and 50°C water-soluble chloride content of horizontal-joined specimens N30-NN and NN were measured according to a JCI potentiometric titration method [12].

3. RESULTS AND DISCUSSION

3.1 Corrosion of steel bars

a) Vertical-jointed specimens

The average values of corrosion loss over the whole surface area of the two steel bars in each vertical-jointed specimen per unit surface area are shown in Fig. 4. Taking into consideration the effect of dissolution of mill scale into the $(NH_4)2HC_6H_5O_7$ solution used according to the JCI method, the measured corrosion loss of the steel bars in vertical-jointed specimen SH, which showed no sign of corrosion, was subtracted from all other measured corrosion losses. Thus, Fig. 4 shows a calculated "true" corrosion loss.

Fig. 5 shows the corroded surface area of the left, central, and right parts of the steel bars, respectively. The corroded area of one-piece specimens is also shown separately with respect to the central part of 300mm length and the left and right parts of 200mm length.

Contrary to the assumption that joints would have a detrimental effect, a comparison of specimens SL-SL-SL and SL, N30-N30 and N30, and NN-NN-NN and NN indicates that the corrosion loss and corroded area percentage were in fact larger in the beams without joints than in the beams with joints. Since the specimens were not kept constantly in contact with the chloride solution, but were sprayed at intervals, this could have caused differences in the penetration of chloride between specimens. Either way, no visual indication of corrosion was seen on steel bars

around the joints in any of the specimens. Therefore, it is concluded that the penetration of chloride ions supplied by spraying was not excessive at joints.

This finding that chloride penetration does not concentrate at joints even if the self-compacting concrete is not vibrated during placing leads us to conclude that the microstructure of concrete at such joints is tight, and this results from the superior self-compactability of self-compacting concrete.

Corrosion losses were particularly large in specimens in which mixture N30 was used for the left and/or right part(s), irrespective of the type of concrete used for the central part. Furthermore, among these specimens, the corroded area was particularly large for sections of steel bars where mixture N30 was placed. Accordingly, the corrosion losses detected in steel bars from these specimens are assumed to have been caused mostly by corrosion in the left and/or right part(s) where mixture N30 was placed.

On the other hand, corrosion losses in specimens in which mixture N15 was used for the left and/or right part(s) and in which no mixture N30 was used were more or less equal to those in specimens with no added chloride at all. Corroded areas of steel bars in parts placed with mixture N15 were, however, generally larger than those in parts where no chloride had been added, and some were even as large as those in parts with mixture N30. The threshold chloride ion density at which rapid corrosion of the reinforcing steel begins is regarded as 1.2~2.5kg/ m³ [8][9]. The chloride content in mixture N15 was 2.75kg/m³, which is slightly above this threshold density. Thus the steel bars have already started to corrode, although not severely. However, it is necessary to continue observing the progress of corrosion in mixture N15, since it appears that the passivation film on the steel bars in mixture N15 has been destroyed, as is clear from Fig. 5, and the corrosion rate may increase hereafter.

In the cases where concrete mixtures of different chloride densities were joined together, steel bar



Fig. 4 Corrosion loss of steel bars (vertical-jointed specimen)



Fig. 5 Corroded area of steel bar (vertical-jointed specimen)

corrosion was often observed in the part with greater chloride density adjacent to the joint. It has been reported that when the chloride contents of joined concrete mixtures surrounding steel bars are different, the entire beam of concrete constitutes a macro-cell, whereby corrosion occurs in the steel bars around the joint [13][14]. Since it is assumed that chloride ions did not penetrate particularly well through the joints, as mentioned above, it is assumed that corrosion of steel bars around joints was caused by this macro-cell phenomenon.

In cases where normal concrete NN and self-compacting concrete SL of normal strength were used for the central part of specimens, corrosion of steel bars was also observed near the joints in the central part. This is attributable to the diffusion of chloride ions from the left and right parts of the beams into the central part.

High-strength self-compacting concrete SH can be considered to have superior corrosion protection properties, because the corroded area in the central part using mixture SH was 0 percent. On the other hand, the corroded area of steel bars in left and right parts joined to a central part placed with mixture SH was as high as in cases where other mixtures were used for the central part. Also the corrosion loss of steel bars in these specimens was not insignificant. It is therefore very important that patch repairs to a concrete structure be carried out only after completely removing chloride-contaminated parts from the structure.

In specimens in which self-compacting concrete SL with normal strength was used for the central part, corrosion of steel bars in the central part was observed. The corroded area was as large as that in the central part when ordinary concrete NN was used. In these cases, it is concluded that the sprayed chloride ions reached the steel bars, or that chloride ions from the left and right parts diffused into the central part. It should be noted, however, that while all specimens made with ordinary concrete NN for the central part suffered steel bar corrosion, the corroded area was 0% in some specimens using self-compacting concrete SL.

It is reported that self-compacting concrete with limestone powder has superior ability to suppress chloride penetration as compared to ordinary concrete of the same strength. Consequently, it is considered that the occurrence of corrosion was delayed in self-compacting concrete SL in the central part of specimens in which no chloride was initially added as compared to the cases in which ordinary concrete NN was used for the central part.

b) Horizontal-jointed specimens

The average values of corrosion loss over the whole surface area of steel bars in the horizontal-jointed specimens per unit surface area are shown in Fig. 6. The amount of corrosion loss of the steel bars in the top part of horizontal-jointed specimen NN, which showed no sign of corrosion, was subtracted from the measured corrosion losses.

Fig. 7 shows the corroded area of steel bars in the top and bottom parts, respectively.

In specimens with a joint comprising mixture N30 for the top part, the corrosion loss was large for steel bars in the top part where chloride ions were present from the start. The corrosion losses of steel bars in the top part of



Fig. 6 Corrosion loss of steel bar (horizontal-jointed specimen)





specimens N30-SL, N30-SH, and N30 were more or less equal, which indicates that the different concrete mixtures making up the bottom part did not substantially affect corrosion in the top part.

Meanwhile, the corrosion losses of steel bars in specimens NN and N30 with a uniform chloride content were larger in the bottom part than in the top part. The chloride distributions in specimens N30-NN and NN at the age of 160 days are shown in Fig. 8. As this shows, chloride contents were lower in the bottom part than in the top part in both specimens.

The reason for the large corrosion loss of steel bars in the bottom part despite this lower chloride content is thought to be that sprayed chloride solution remained around the bottom of specimens, as mentioned before, and that the corrosion reaction accelerated in the bottom part after the passivation film was lost. Furthermore, it is assumed that there was an abundant oxygen supply through the concrete cover in the top part, as a result of which the steel bars in the top part acted as the cathode of a macro-cell.

As with corrosion loss, the corroded area of steel bars in the top part of specimens with horizontal joints was larger than in the bottom part, except in the case of specimen N30-NN. On the other hand, the corroded area of steel bars in the bottom part of specimens without joints was larger than in the top part.

As for specimen N30-NN, corrosion loss in the bottom part was larger than with other specimens, and the corroded area of steel bars in the bottom part was larger than in the top part. Since no chloride was added to the concrete used for the bottom part of this specimen, the steel corrosion in this part is thought to have been caused by the sprayed chloride solution. As noted above, once the passivation film has been destroyed, the bottom part of specimen is more susceptible to corrosion. It is therefore concluded that the passivation film was destroyed at an early age in the bottom part of specimen N30-NN, consisting of ordinary concrete, which is inferior in its ability to suppress chloride penetration to self-compacting concrete [8], resulting in large corrosion loss of steel bars in the bottom part.

In the bottom part of specimen N30-SH, consisting of mixture SH with a low water-binder ratio, corrosion loss was not zero. However, corrosion was not noted visually on the steel in this part, so the corroded area of the steel bars in this part was 0%. It can therefore be concluded that steel in this part was not corroded at all [15].

A comparison of specimens N30-NN and N30-SL, in which mixtures of the same water-binder ratio were used for the bottom part, indicated that corrosion loss in the top part of specimen N30-SL consisting of mixture N30 was larger than that in the top part of specimen N30-NN consisting of same mixture N30, while corrosion loss in the bottom part of specimen N30-SL consisting of mixture SL was smaller than that in the bottom part of specimen N30-NN consisting of mixture NN. The reason for these results will be discussed below.

3.2 Macro-cell corrosion

a) Macro-cell current

Macro-cell current in horizontal specimen is shown in Figs. 9 and 10. As can be seen from these figures, macro-cell



current flowed from the bottom part to the top part of specimens at early ages, except in the case of specimen N30. It is therefore assumed that a macro-cell circuit was formed by the steel bars in the top and bottom parts, which acted as anode and cathode, respectively.

The current in specimen N30-NN, in which ordinary concrete NN was used for the bottom part, reversed at 40~80 days of age, after which the steel bar in the bottom part began to act as the anode of the macro-cell circuit. Moreover, the macro-cell current was larger than previously.

The halfcell potential and index of corrosion rate of steel bars in specimen N30-NN are shown in Figs. 11 and 12 respectively. ASTM C 876 was used here to assume steel corrosion [16].

-80mV < E	: 95% no corrosion
$-230mV < E \le -80mV$: uncertain
$E \leq -230 mV$: 95% corrosion

where :

E: halfcell potential of steel bar (vs. saturated silver chloride electrode)

The reciprocal of polarization resistance is defined as the index of corrosion rate in this study [17], as there is the following correlation between corrosion loss and polarization resistance of steel bars, assuming that iron turns fully into divalent ions during the corrosion reaction :

$$G = \frac{M}{2F_a} \int I_{corr} dt = K \times \frac{M}{2F_a} \times \int \frac{1}{R_p} dt$$

where :

G : corrosion loss (g/cm²) M : atomic mass of iron (=55.8) F_a : Faraday constant (=96500C) I_{corr} : corrosion current density per unit surface area of steel bar (A/cm²) R_p : polarization resistance (Ω •cm²) K : constant (V)

The halfcell potential of steel bars in the bottom part of specimen N30-NN remained in the "uncertain" or "no corrosion" area until the age of 60 days. It became base thereafter, and became baser than the top part. Similarly, the index of corrosion rate for steel bars in the bottom part of specimen N30-NN was smaller than that in the top part







until the age of 80 days, and thereafter, in some specimens, it was even larger than in the top part. It can be considered that corrosion of steel bars began to occur in the bottom part around the age of 60 days, after which the corrosion rate increased more rapidly in the bottom part than in the top part. This may be attributable to the high humidity in the bottom part, as mentioned before.

Although not shown in the figures, the halfcell potential and the index of corrosion rate in the bottom part of specimen NN had a similar tendency, i.e. they both changed suddenly at the age of 60 days. Also, the same phenomenon was observed in specimen N30-SL at the age of 150 days.

It is reported that self-compacting concrete with limestone powder is superior in chloride-blocking performance than ordinary concrete of the same strength [7]. In this study, mixture SL is a self-compacting concrete of compressive strength almost the same as mixture NN. Therefore, it is supposed that chloride ions reached the steel bar in mixture SL slower than in mixture NN.

Furthermore, the halfcell potential and the index of corrosion rate of steel bars in the bottom part of specimen N30-SH, in which mixture SH with a low water-binder ratio was used, indicate that steel corrosion did not occur. It can therefore be concluded that mixture SH has superior chloride-blocking performance.

b) Estimation of macro-cell corrosion loss

Macro-cell corrosion loss in horizontal-jointed specimens can be calculated from equation 1, provided the measured macro-cell currents are all attributable to the macro-cell corrosion reaction. Macro-cell corrosion losses until the age of 160 days obtained in this way are shown in Fig. 13.



Fig. 11 Halfcell potential of steel bar (horizontal-jointed speecimen N30-NN)



Fig. 12 Index of corrosion rate of steel bar by rectangular pulse method (horizontal-jointed speecimen N30-NN)

In specimen N30, in which the macro-cell current was very large, macro-cell corrosion loss of steel bars is assumed to be much lager in the bottom part than in other specimens. Comparing specimens N30-NN and NN, in which the same mixture NN was used for the bottom part, the macro-cell corrosion losses of steel bars in the bottom part were the same, although the initial chloride contents in the top part were different. The bottom part of specimens was subject to more severe steel corrosion, as discussed above. However, these results indicate that macro-cell corrosion loss in the bottom part does not depend on the initial chloride content in the top part of a specimen.

Further, the ratios of macro-cell corrosion losses to overall corrosion losses were not so large in the top part of specimens N30-NN, N30-SL and N30-SH, in which mixture N30 with chloride ions was used.



Fig. 13 Calculated macro-cell corrosion loss of steel bar

Generally, the rate of the corrosion reaction is governed by the volume of oxygen available [18] and by the effect of concrete

resistance on the transfer of electric charges. Therefore, the tight microstructure of low water-binder ratio concrete can be advantageously used for the purpose of corrosion proofing, as it reduces the transmission of oxygen and increases electrical resistance. The macro-cell current was much lower in specimen N30-SH in this study than that in other specimens, as shown in Figs. 9 and 10, indicating that mixture SH did in fact have the effect of suppressing macro-cell corrosion.

However, corrosion loss also includes micro-cell corrosion of steel bars, and the overall corrosion loss of steel bars in the top part of specimen N30-SH was not reduced as compared to other specimens as a result of micro-cell corrosion loss (see Figs. 6 and 7).

In specimens in which self-compacting concrete SL and ordinary concrete NN of the same water-binder ratio were used for the bottom part, macro-cell corrosion loss of steel bars in the top part was larger in specimen N30-NN than in specimen N30-SL. This is partly because steel in the top part of specimen N30-SL was subject to macro-cell corrosion for a longer period of time as the anode of a macro-cell, as shown Figs. 9 and 10. However, the macro-cell current during this period was almost the same in both specimens. Accordingly, it is concluded that self-compacting concrete SL deters the occurrence of corrosion as compared to ordinary concrete NN of the same water-binder ratio, but does not suppress the macro-cell reaction, unlike self-compacting concrete SH with a low water-binder ratio, after the occurrence of corrosion.

3.3 Relationship between macro-cell corrosion and micro-cell corrosion

a) Study of constant K

In the case of horizontal-jointed specimens, polarization resistance was measured with the steel bars in the top and bottom parts disconnected from each other.

Examples of corrosion rate index of steel bars in the horizontal specimens are shown in Table 5; indexes obtained

with the cables connected to steel bars in the top and bottom parts connected to each other, and those 20 minutes after disconnecting the cables, are both shown for the purpose of comparison.

As shown in the table, corrosion rates were different depending on whether the steel bars in the top and bottom parts were electrically connected or not. Polarization resistance measurements made with the top and bottom steel bars connected are assumed to reflect both macro-cell and micro-cell corrosion reactions. On the other hand, when **Table 5** Examples of index of corosion rate for N30-SL with rectangular pulse method using two methods : (1) steel bars were connected together, (2) steel bars not connected ($1/k\Omega/cm^2$)

	connected	separated
T part	0.476	0.072
B part	0.101	0.034

the cables are disconnected, only micro-cell corrosion occurs, so the measured polarization resistance represents only the micro-cell corrosion reaction [11]. The difference in polarization resistance is assumed to result from this.

In this study, polarization resistance was measured within about 5 minutes of the cables being disconnected. It is thought that polarization resistance does not change immediately after disconnection, but stabilizes gradually over a certain period of time [19]. In this study, however, the measured polarization resistance of the horizontal-jointed specimen was presumed to represent only the micro-cell corrosion.

Based on the assumption that the difference obtained by subtracting macro-cell corrosion loss shown in Fig. 13 from the corrosion loss of a horizontal-joined specimen represents the micro-cell corrosion loss, constant K for horizontal-jointed specimen is 0.0151(V) according to equation (1), provided that the polarization resistance measured by the double rectangular and AC impedance methods corresponds only to micro-cell corrosion.

In the case of vertical-jointed specimens, it is difficult to distinguish micro-cell corrosion loss from macro-cell corrosion loss. Moreover, the polarization resistance of vertical-jointed specimen corresponds to values for horizontal-jointed specimens measured by the double rectangular and AC impedance methods with the cables connected. Constant K for vertical-jointed specimen was thus calculated from the relationship between corrosion loss shown in Fig. 4 and polarization resistance, this being 0.0278(V).

b) Horizontal-jointed specimens

The progress of macro-cell corrosion loss obtained from the macro-cell current shown in Fig. 9 and the progress of micro-cell corrosion loss calculated from constant K as obtained above for steel bars in horizontal-jointed specimens are shown in Fig. 14. In calculating corrosion loss from polarization resistance, the value 0.0151(V) was adapted as constant K. The corrosion losses shown here are obtained through calculation and do not correspond to the measured losses shown in Fig. 6.

As already noted, the bottom part of specimens remained wet and were subject to more severe steel corrosion than to the top part. Accordingly, hardly any macro-cell corrosion was observed in the top part of horizontal specimens.

While corrosion in the top part of specimens is mostly caused by micro-cell effects, the ratio of macro-cell corrosion loss to overall corrosion loss was large in the bottom part, except in the case of specimen N30-SH. The ratio of these values for each specimen is in descending order : N30-NN > N30-SL > N30-SH=0%.





It should be noted that macro-cell corrosion loss was calculated also from macro-cell current across steel bars in the top and bottom parts in this study, while it is assumed that a macro-cell circuit is also formed between steel bars in the same part. The actual macro-cell corrosion loss may therefore be larger than the values shown in Figs. 13 and 14.

Since the macro-cell current in specimens N30-NN and N30-SL continue to increase, as shown in Fig. 9, it is necessary to continue the investigation to clarify if macro-cell corrosion is affected by differences in chloride penetration rate, or in concrete electrical resistance, or in permeability to oxygen.

It has been ascertained, however, that self-compacting concrete and ordinary concrete with the same strength have different effects on the occurrence and progress of chloride-induced steel corrosion, and also of macro-cell.

c) Vertical-jointed specimens

Since the investigation of horizontal-jointed specimens indicated that the formation of a macro-cell significantly affects corrosion, macro-cell corrosion was also studied in the vertical-jointed specimens. With respect to the specimens where the left and right parts consist of mixture N30 and the central part consists of mixture NN or SL, the corroded area of steel bars in the central part was close to 0%, and thus the corrosion loss in the central part of these specimens is assumed to be 0g. In the case of specimens using mixture N15 for the left part and where the right part consists of mixture N30, the corroded area in the N15 part was large. However, since the corrosion losses of steel bar in specimens N15-NN-N15, N15-SL-N15, and N15 were negligible, the corrosion loss in the N15 part can be regarded as 0g. In other words, corrosion losses in these specimens are all attributable to the N30 part. Thus, the corrosion losses are shown in Fig. 15 per unit surface area of steel bar in the N30 part.

As compared to specimen N30-N30, in which the chloride content was uniform and a macro-cell circuit was not formed, the corrosion loss of steel bars in the mixture N30 part was larger in other specimens. Assuming that the corrosion loss in these specimens in an amount equal to that of N30-N30-N30 is due to micro-cell corrosion, the excess corrosion loss can be attributed to macro-cell corrosion loss.

The macro-cell corrosion obtained from vertical-jointed specimens was larger than that in horizontal-jointed specimen. This is considered to be because of the difference in shape, reflected in the difference in distance between anode and cathode in these specimens. Another reason may be that the steel bars in the vertical-jointed specimen were equidistant from the bottom of the specimen, while the horizontal-jointed specimens were subject to an environment that differed with respect to the top part and the bottom part. Thus, macro-cell corrosion concentrated in the left and right parts of vertical-jointed specimens, that had initially contained chloride.

The corrosion loss of steel bar per unit area was smaller in specimens where mixture N30 was used for both left and right parts than in specimens in which mixture N15 was used for the left part and mixture N30 was used for the right

part. Considering that hardly any corrosion loss was detected in specimen N15, it is assumed that the steel bars in mixture N15 acted as the cathode of a macro-cell in the latter. It can therefore be concluded that the left part consisting of mixture N15 and the central part acted as the cathode of a macro-cell circuit in the case of specimens N15-NN-N30 and N15-SL-N30. On the other hand, in the case of specimens N30-NN-N30 and N30-SL-N30, it is considered that only the central part acted as a cathode, whereby the amount of oxygen available to the cathode was different from that in specimens N15-NN-N30 and N15-SL-N30, resulting in the difference in corrosion loss.

Next, a comparison is made between the cases in which self-compacting concrete and ordinary concrete of the same water-cement ratio were used, respectively, for the central part. The corrosion loss of steel bar per unit area in the left and right parts consisting of mixture N30 was larger in specimens in which self-compacting concrete SL was used for the central part than in specimens using ordinary concrete



Fig. 15 Calculated macro-cell corrosion loss of steel bar (vertical-jointed specimen)

NN. As already noted above, macro-cell corrosion loss in the mixture N30 part was larger in horizontal-jointed specimen N30-SL than in N30-NN. The corroded area of steel bar in the left part of N15-SL-N15 was about 12%, while it was about 2% in the left part of specimen N15-SL-N30, as shown in Fig. 5. It is considered that the steel bars in mixture N15 were most base in specimen N15-SL-N15, thus acting as the anode of a macro-cell circuit, whereas steel bars in mixture N30 were most base in specimen N15-SL-N30, so the corroded area of steel bar in mixture N15 was not so large.

Similarly, cases in which self-compacting concrete SL and ordinary concrete NN were used, respectively, for the central part of specimens are compared next. It is reported that self-compacting concrete with limestone powder is superior to ordinary concrete in resistance to chloride penetration [7]. Accordingly, loss of the passivation film in the central part with mixture SL is assumed to be less than that with mixture NN. The results shown in Fig. 5, indicating that the corroded area of steel bar in mixture SL was smaller than that in mixture NN, back up this assumption. It is, therefore, concluded that the difference in halfcell-potential between steel bars in the central part and those in the left and right parts was large, in consequence of which macro-cell corrosion current and corrosion loss in the left and right parts were accordingly large.

Self-compacting concrete SL has a tighter microstructure than ordinary concrete NN of the same strength, and thus as already noted it is considered to have superior chloride-proofing performance. The occurrence of steel corrosion due to external chlorides might have been delayed by this property of self-compacting concrete (see Fig. 9 to Fig. 10).

On the other hand, the corrosion rate of steel bars is assumed to be affected by the supply of oxygen required for the cathode reaction [18] and by the electric resistance of the concrete, which controls the mobility of electric charges, particularly in the case of macro-cell corrosion.

It is, however, reported that oxygen permeability is not significantly affected by water-cement ratio. Specifically, the oxygen supply in the case of W/C=30% falls only by 3/5 with respect to the case of W/C=50% [20]. The concrete resistance of mixture SL measured in this study with a current of 10μ A~1mA and frequency of 800Hz was nearly equal to that of mixture NN. It can therefore be concluded that the amount of supplied oxygen and concrete resistance in macro-cell corrosion in mixture SL and NN are substantially the same.

Consequently, it is deduced that while the tightness of the microstructure of self-compacting concrete SL does have an influence on delaying the occurrence of steel corrosion in the part made with self-compacting concrete SL, when contiguous concrete contains chloride ions and self-compacting concrete acts as the cathode of a macro-cell circuit with respect to this adjacent concrete, the macro-cell corrosion occurs in the adjoining part even more severely than in parts adjoining ordinary concrete.

In summary, when repairing an RC structure using self-compacting concrete, it is absolutely necessary to remove all existing chloride-contaminated areas completely, since there is the risk that macro-cell corrosion may even be accelerated as compared to the case in which ordinary concrete is used, as noted above in section 3.1. The design of repair work thus entails a consideration of the electrochemical compatibility between existing members and new parts.

4. Conclusion

This study entailed an investigation of the progress of steel corrosion in model specimens. Three types of specimens were prepared, with ordinary concrete and two types of self-compacting concrete patched to chloride-contaminated ordinary concrete.

The results obtained in this study can be summarized as follows :

(1) Corrosion loss of steel bars does not increase, while corroded area does, if chloride ions are added to the cover concrete in an amount of 2.75kg/m³.

(2) Self-compacting concrete is superior to normal concrete of the same compressive strength in protecting steel bars from chloride-induced corrosion, and also in delaying the deterioration of steel bars in the self-compacting concrete part.

(3) Macro-cell corrosion occurs more severely in chloride-contaminated parts adjoining self-compacting concrete patches than in chloride-contaminated parts adjoining ordinary concrete patches.

Future investigations should take into consideration the ambient conditions of specimens. It should be noted that in these experiments all specimens were held on wooden spacers with the placement surface upwards, and chloride solution was sprayed from above onto the placement surface. In actual practice, however, water and chloride ions are likely to penetrate into concrete from the bottom surface of a structure.

Furthermore, although the ratio of anode area and cathode area in a macro-cell circuit was presumed to be constant in this study, it in fact varies with conditions. Further, the water content in concrete would differ under various ambient conditions. Therefore, these factors also should be taken into consideration in future.

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