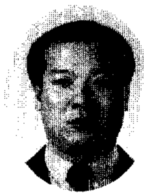
방식재를 사용한 철근 콘크리트의 철근부식에 관한 실험적 연구

Experimental Studies on the Corrosion of Reinforcement Steel in Reinforced Concrete with Corrosion Inhibitors

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ABSTRACT

Recent construction activities and maintenance of marine facilities have been accelerating to keep up with rapid economic growth in Korea. Marine concrete structures are exposed to salts and chloride from ocean environments. The corrosion of reinforcement steel caused by chloride-penetration into concrete may severely affect the durability of concrete structures. The objective of this research is to develop a durable concrete by investigating the corrosion resistance of various corrosion protection systems using different water/cement ratio, silica fumes, corrosion inhibitors and etc. A two-year verification test on various corrosion protection systems has been done in the laboratory and at the seaside. As a pilot test, 60 reinforced concrete specimens were subjected to cyclic wet and dry saltwater exposures in 40 weeks. And further corrosion investigations

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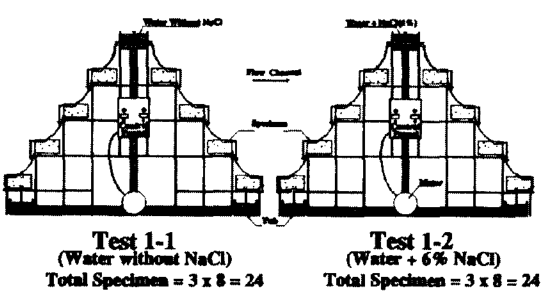
on reinforcement steel are now under progress for more than 150 concrete specimens. Corrosion-related measurements include macrocell corrosion current, instant-off voltage between corroding and noncorroding reinforcement, chloride contents, the corroded surface areas on the reinforcement steel, and etc. A low level of corrosion is investigated on reinforcement steels in concrete specimens made with corrosion inhibitors or applied aqueous impregnating corrosion inhibitors into their surface, even though high chloride contents of concrete specimens.

Keywords : Corrosion Current, Corrosion Inhibitors, Corrosion Protection System, Chloride-Penetration, Marine Concrete, Reinforcement Steel

1. Introduction

This research is to develop appropriate corrosion protection systems for reinforcement steel embedded in marine concrete, which have been done by evaluating material properties and performance of various corrosion protection systems for two years. Pilot tests have been done on a total of 60 specimens. Analyzing and evaluating the result of pilot test, further rapid corrosion test is now under progress on 81 beam molds and 72 slab molds in the laboratory. In addition, 9 beam molds were placed at the seaside to confirm the corroded surface area on reinforcement steel on every 3 months. Table 1 shows the program of overall rapid corrosion test to be performed for two year.

Type I portland cement was used with a water-cement ratio of 0.5 or 0.6. Six brands of corrosion inhibitors have been used for the test. Corrosion inhibitors used are categorized into two types: one with additives for concrete mortar, and the other with aqueous impregnators to be applied on concrete surface. All the pilot specimen were subjected to cyclic wet and dry saltwater exposures in above 40 weeks. For further rapid test now under progress, some beam molds are placed to atmosphere, and other beams are exposed to cyclic water or 6% NaCl solution in the laboratory. And some slab molds are also placed to atmosphere, and other slabs are ponded with water or 6% NaCl solution on their top surface. So as to simulate marine environments in the tidal



(a) For Cyclic water (b) For Cyclic 6% NaCl Solution

(c) Photograph of Test Setup

Fig. 1 Test Setups for Cyclic Water or 6% NaCl Solution for Ongoing Test

Table 1 Overall Rapid Corrosion Testing Program

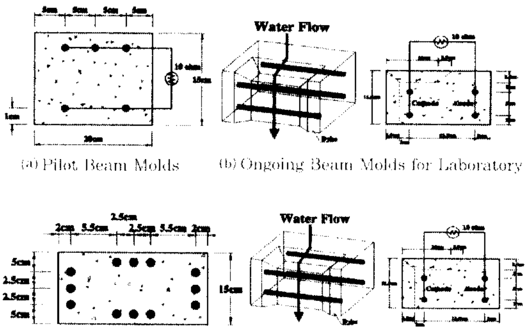
	Pilot Test	Ongoing Test	
	Pilot Beam Molds	Beam Molds	Slab Molds
Size	20cm(W)×15cm(B) ×20cm(H)	20cm(W)×20cm(B) ×11.5cm(H)	30cm(W)×30cm(B) ×10cm(H)
Number of Specimens	60(LAB)	81(LAB) + 9(SEASIDE)	72
Number of Mixas	20	9	8

zone, two special test setups have been designed and made as shown in Fig. 1.

A schematic of concrete specimens chosen for rapid corrosion test is shown in Fig. 2. The specimen contain anodic steel bars in a concrete that gradually absorb moisture and chloride from cyclic saltwater. The cathodic steel bars remain in a relatively chloride-free concrete environment. The ends of the anodic and cathodic steel bars are connected externally so that the flow of corrosion current, Ic, between the cathodic and anodic levels can be measured. This connection is made at the Data Logger with a 10 ohm resistor. Corrosion-related measurements are macrocell corrosion current, instant-off voltage between corroding and noncorroding reinforcement, periodic chloride contents of test specimens, the corroded surface areas on the reinforcement steel and etc. All the measurements for corrosion protection systems will have been compared to evaluate their performance and effectiveness.

2. Pilot Rapid Corrosion Test

Pilot rapid corrosion testing has been done in the laboratoty for one year. A total of 60 specimens were made having a water-cement ratio of 0.5 or 0.6. Mixing water was 0.1% NaCl solution, and marine sand was used to induce rapid corrosion of reinforcement steel. 13mm crushed stones were used for coarse aggregate. Cover depth for the



(a) Pilot Beam Molds (b) Ongoing Beam Molds for Laboratory

(c) Ongoing Beam Molds at the Seaside (d) Ongoing Slab Molds for Laboratory

Fig. 2 Concrete Specimen for Rapid Corrosion Test

anodic steel bars was 1 cm to induce rapid corrosion, but that for cathodic steel bars were 2 cm to remain in a relatively noncorrosive state. The concrete compressive strength, σ_{ck}, was obtained by testing specifically cured cyclinders with a diameter of 100 mm and a height of 200 mm, of which results are summarized in Table 2. All the specimens were placed on the test setup, which were specially designed to simulate the exposure condition of marine concrete structures in the tidal zone, as shown in Fig. 1.

Fig. 5 shows corrosion rate of reinforcement steel embedded in normal concrete, specimen labelled "NS".

Fig. 3 and Fig. 4 show corrosion current for concrete specimens treated with corrosion inhibitors. At the end of test, the corroded surface area of reinforcement steel embedded in concrete was sketched in expanded figure. Fig. 6, Fig. 7 and Fig. 8 show the expanded figure of the corroded surface area for representative concrete specimen. Pilot test has led to the following conclusion that the level of corrosion was developed in relatively low on anodic reinforcement steels embedded in concrete made with corrosion inhibitors or applied aqueous impregnating corrosion

Table 2 Mix Proportions and Compressive Strength for Various Concrete Specimens

Specimen		Specimen Designation	W/C (%)	Air Content (%)	Slump (cm)	Compressive Strength (kgf/cm^2)	
						7 Days	28 Days
Normal Strength		NS6	60	4.8~6.2	11.5~17	86	142
		NS5	50			145	206
Mixture	Special Cement	MC6	60			107	145
		MC5	50			173	237
	Rice Bean	MR6	60			100	148
		MR5	50			160	217
	Silica Fume	MS6	60			94	150
		MS5	50			152	228
Corrosion Inhibitors	For Additive	CI/AA6	60			94	113
		CI/AA5	50			92	151
		CI/AB6	60			62	92
		CI/AB5	50			86	127
		CI/AC6	60			83	118
		CI/AC5	50			96	156
		CI/AD6	60			56	93
		CI/AD5	50			95	146
	For Impregnator	CI/IA	60			86	124
		CI/IB				86	124
		CI/IC				86	124
High Strength		HS	33.3	1.8	20.8	375	445

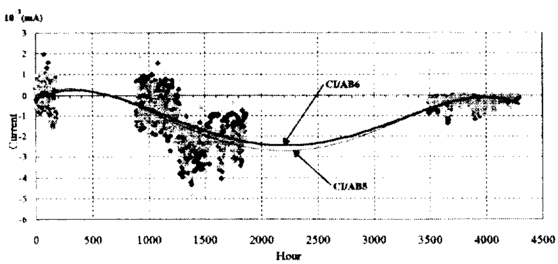


Fig. 3 Corrosion Current for Concrete Specimens with Corrosion Inhibitors Labelled in CI/AB5 and CI/AB6

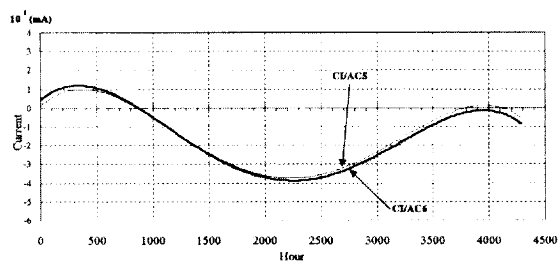


Fig. 4 Corrosion Current for Concrete Specimens with Corrosion Inhibitors Labelled in CI/AC5 and CI/AC6

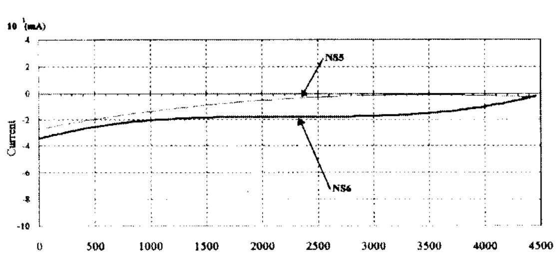


Fig. 5 Corrosion Current for Concrete Specimens without Corrosion Inhibitors Labelled in NS5 and NS6

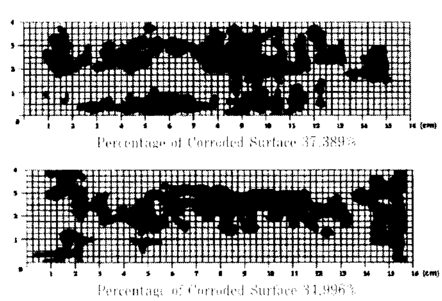


Fig. 6 Corroded Surface Area for Reinforcement Steel in Concrete Specimens Labelled in CI/AB6

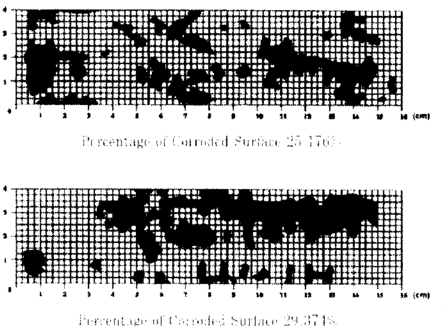


Fig. 7 Corroded Surface Area for Reinforcement Steel in Concrete Specimens Labelled in CI/AC5

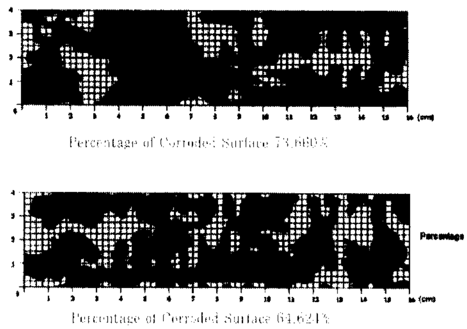


Fig. 8 Corroded Surface Area for Reinforcement Steel in Concrete Specimens Labelled in NS6

inhibitors on its surface, comparing with that for normal concrete made without treating corrosion inhibitors.

3. Ongoing Rapid Corrosion Test

Further rapid corrosion test is now under progress in the laboratory and at the seaside with supplementing a couple of deficiencies met with during the pilot test. Ongoing rapid corrosion test has been done on two types of specimen such as 81 beam(cube) molds and 72 slab molds as shown in Fig. 2. Beam molds are placed under three different exposure conditions, such as 1) cyclic 6% NaCl solution, 2) cyclic water and 3) normal atmosphere. Two test setups have been used to make concrete specimen exposed in cyclic wet saltwater and dry saltwater on every 12 hours by installing a timer, of which role is to simulate marine environments in the tidal zone. In addition, 9 beam specimens in corresponding mix have been located near the seaside and visually confirmed actual corrosion state by extracting reinforcing steels from concrete specimen, of which test results have been compared with experimental corrosion level on corresponding beam molds. Corrosion on reinforcement steels in slab molds have also been measured under above three exposure conditions, but 6% NaCl solution and water have been ponded in the top of slab with dykes on four edges.

3.1 Beam Molds

As shown in Table 3, 10 specimens(20cm×20cm×11.5cm) per each mix have been made for 9 at the laboratory and 1 at the seaside. Laboratory specimens include 3 for air exposure, 3 for water exposure and 3 for 6% NaCl exposure. 6 corrosion inhibitors have been provided by 3 different companies. 13mm crushed stone was used for coarse aggregate from Ansung pit. And mixing water was mixed with 0.1% NaCl to absolute dry weight of fine sand to accelerate rapid corrosion of reinforcing steel. Type I portland cement was used, and CSF-90 silica fume was also used to increase compressive strength for some concrete specimens. Summary of all beam specimens are tabulated in Table 3, which shows mix proportions and compressive strength for each batch.

3.2 Slab Molds

The slab specimen is 300mm wide, 300mm

Table 3 Mix Proportions and Compressive Strength for Beam Molds

Specimen		Specimen Designation	W/C (%)	Air Content (%)	Slump (cm)	Compressive Strength (kgf/cm²) 28 Days
Normal Strength		B-NS-A(3), B-NS-W(3) B-NS-N(3), B-NS-S(1)	60	4.4~9	16~20	247
Mixture	Silica Fume	B-SF-A(3), B-SF-W(3) B-SF-N(3), B-SF-S(1)	60	4.4~9	16~20	-
Corrosion Inhibitors	For Additive	B-GR/M-A(3), B-GR/M-W(3) B-GR/M-N(3), B-GR/M-S(1)	60	4.4~9	16~20	251
Corrosion Inhibitors	For Additive	B-SK/M-A(3), B-SK/M-W(3) B-SK/M-N(3), B-SK/M-S(1)	60	4.4~9	16~20	291
Corrosion Inhibitors	For Additive	B-MC/M-A(3), B-MC/M W(3) B-MC/M-N(3), B-MC/M-S(1)	60	4.4~9	16~20	232
Corrosion Inhibitors	For Impregnator	B-SK/P-A(3), B-SK/P-W(3) B-SK/P-N(3), B-SK/P-S(1)	60	4.4~9	16~20	247
Corrosion Inhibitors	For Impregnator	B-MC/P-A(3), B-MC/P-W(3) B-MC/P-N(3), B-MC/P-S(1)	60	4.4~9	16~20	247
High Strength		B-HS-A(3), B-HS-W(3) B-HS-N(3), B-HS-S(1)	38	2.1	16~20	534

Note : In specimen designation, the first character denotes mold type("B" for beam and "S" for slab), the middle characters denote specimen type("NS" for normal strength, "HS" for high strength, "SF" for silica fume, "GR, SK/M and MC/M" for Corrosion Inhibitor for additive, "SK/P, MC/P and HD" for Corrosion Inhibitor for impregnators) and the last character specifies the exposure condition("A" for air exposure, "W" for water exposure, "N" for NaCl solution exposure and "S" for the exposure at the seaside).

long, and 100mm high. Concrete is poured in two steps. Concrete in bottom layer was mixed with 0.1% Nacl solution, but concrete in top layer was mixed with 0.3% NaCl solution to accelerate corrosion in the anodic steels. The top of the specimen is crowned by an acrylic dyke that retains salt water or water. The sides of the specimen are coated with epoxy to prevent salt intrusion from the sides. Two mats of steel are provided in concrete. The top layer of steel serves as the anode, and the bottom layer of steel serves as the cathode. The top and bottom layers of steel extend from the sides of the concrete so that an external electrical connection can be made between the two layers. This connection is made at a Data Logger with a 10 ohm resistor. The macrocell corrosion current is monitored weekly by measuring the voltage drop across the resistor.

A total of 72 specimens have been made for 8 batches(9 specimens per each batch). 3 types of corrosion inhibitors are provided from three different companies. Each corrosion inhibitor has been used in 3 dosages such as an amount of 0.5, 1.0 and 2.0 times of normal dosage recommended by the maker. Table 4 and Fig. 2(d) show summary of slab test specimens.

3.3 Brief Corrosion Test Result

All specimens in the laboratory have the anodic steel bars and the cathodic steel bars, which extend and connect through an electrical cords to the Data Logger with a 10 ohm resistor to measure corrosion potential of embedded reinforcement steel. Corrosion related measurements include macrocell corrosion current, instant-off voltage between corroding and noncorroding

Table 4 Mix Proportions and Compressive Strength for Slab Molds

Specimen		Inhibitors Dosage	Specimen Designation	W/C (%)	Air Content (%)	Slump (cm)	Compressive Strength (kgf/cm²)
							28 Days
Normal Strength		-	S-NS-A(3)	60	5.2~9.6	19~23	171
			S-NS-W(3)				
			S-NS-N(3)				
Corrosion Inhibitors	For Additive	0.5×Normal Dosage	S-GR/M-A(3)				178
			S-GR/M-W(3)				
			S-GR/M-N(3)				
		1.0×Normal Dosage	S-GR'/M-A(3)				183
			S-GR'/M-W(3)				
			S-GR'/M-N(3)				
		2.0×Normal Dosage	S-GR''/M-A(3)				183
			S-GR''/M-W(3)				
			S-GR''/M-N(3)				
		0.5×Normal Dosage	S-SK/M-A(3)				172
			S-SK/M-W(3)				
			S-SK/M-N(3)				
		1.0×Normal Dosage	S-SK/M'-A(3)				170
			S-SK/M'-W(3)				
			S-SK/M'-N(3)				
		2.0×Normal Dosage	S-SK/M''-A(3)				147
			S-SK/M''-W(3)				
			S-SK/M''-N(3)				
	For Impreghation		S-HD-A(3)				
			S-HD-W(3)				
			S-HD-N(3)				

Note : In specimen designation, please refer to Note of Table 3.

reinforcement, which are investigated every week. Further corrosion measurements are three electrode linear polarization, which has generally become a valuable field tool in a diagnostic and rehabilitation work on a variety of RC structure. Chloride contents of concrete specimen has been evaluated at the initiation of corrosion and at the conclusion of the test cycle. Other specimens in corresponding mix are placed at the seaside near the local power plant. Actual corrosion state will be visually confirmed on every 3 months after sawing concrete specimens. Visual results for corroded surface of specimen

Table 5 I_{corr} for slab molds by 3LP Test

	Air Condition					Water Condition					Nacl Condition				
	1st	2nd	3rd	4th	5th	1st	2nd	3rd	4th	5th	1st	2nd	3rd	4th	5th
S-NS	1.469	1.174	1.256	1.237	1.510	1.680	1.429	1.608	1.858	2.297	1.915	1.451	1.598	2.179	2.274
S-GR	1.298	1.218	1.066	1.170	1.243	1.598	1.558	1.103	1.801	1.905	1.971	1.951	1.550	2.179	2.087
S-GR'	1.671	1.401	1.072	1.346	1.263	1.346	1.120	1.513	1.721	1.854	1.535	1.684	1.050	2.008	2.082
S-GR''	1.689	1.417	1.072	1.373	1.482	1.268	1.153	1.113	1.488	1.759	1.709	1.678	1.799	1.963	2.324
S-SK/M	1.861	1.308	1.101	1.357	1.489	1.713	1.591	1.496	2.213	1.824	1.637	1.415	1.461	1.922	2.172
S-SK/M'	1.392	1.306	0.942	1.230	1.468	1.478	1.466	1.364	2.199	1.870	1.757	1.709	1.680	2.112	2.270
S-SK/M''	1.772	1.373	1.145	1.535	1.537	2.124	1.473	1.617	2.258	2.086	1.918	2.014	1.624	2.269	2.405

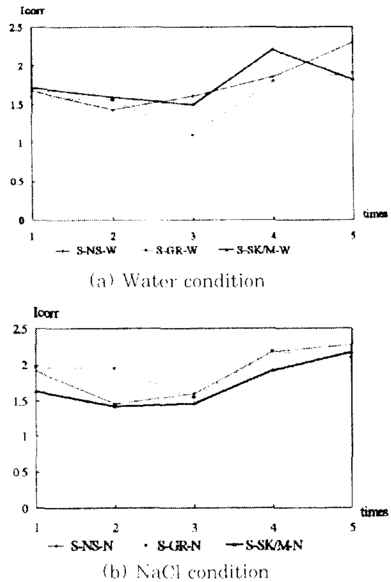


Fig. 9 I_{corr} for Test Specimen with Various Corrosion Inhibitors

Table 6 Evaluation of Corrosion Rate by I_{corr}

I_{corr}	Evaluation
Icorr less than 0.20 mA per sq.ft	no corrosion damage expected
Icorr between 0.20 and 1.0 mA per sq.ft	corrosion damage possible in the range of 10 to 15 year
Icorr between 1.0 and 10 mA per sq.ft	corrosion damage expected in 2 to 10 years
Icorr express of 10 mA per sq.ft	orrosion damage expected in 2 years or less

placed at the seaside site specimen will be evaluated and compared with those for corresponding laboratory specimen. Table 5 and Fig. 9 show the result of polarization test which have been obtained on slab specimen so far. It could be noted from these 3LP test results that some corrosion inhibitors are more or less effective for anticorrosion of reinforcement steel.

Meantime, Table 6 shows the guidelines which emerge for use in data interpretation by assuming constant corrosion rates with time. These guidelines could be used for the evaluation of corrosion rate of reinforcement steel embedded in reinforced concrete structure.

4. Conclusions and Future Works

Conjecturing from the result of pilot test, it is determined that corrosion inhibitors more or less contribute to reduce corrosions on reinforcement steels embedded in marine concrete even though high chloride contents of concrete specimens, but further investigations should be made for any unfavorable effects on concrete durability and etc. As shown in Fig. 6 through Fig. 8, visual corroded surface areas of reinforcing steel in concrete specimen with corrosion inhibitors are smaller than those for other concrete specimen without corrosion inhibitors. These phenomena are good agreement with the conclusion from Fig. 3 through Fig. 5, which show macro corrosion current for concrete specimen.

However, it should be difficult to detect the initiation time for corrosion of reinforcement steel, which could be available from further ongoing rapid corrosion test now under progress.

5. Acknowledgements

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요 약

경제성장에 따른 항만구조물의 건설 및 유지관리에 관한 관심이 급격히 고조되고 있다. 이러한 항만구조물은 해양환경에 노출되어 콘크리트에 매입된 철근의 부식을 야기시키는 요인에 접해있다. 한편, 콘크리트 내부의 염분침투는 매입철근의 부식을 가속화시켜 콘크리트 구조물의 내구성에 상당히 큰 피해를 입힐 수 있다.

본 연구의 목적은 여러 가지 방식제를 사용함과 동시에 물/시멘트를 달리한 실험변수를 이용한 시험체에 대한 부식평가 및 매입철근의 적절한 부식방지 기법의 개발에 있다. 해양환경 조건을 simulation한 해수 및 담수 순환장치를 이용한 실내 시험체의 철근 부식도 평가 및 항만현장에 직접 거치된 시험체 등 다양한 조건하의 2년간의 실험이 현재 진행 중에 있다. 40주에 걸처 간헐 침투되는 해수조건에서 60개의 콘크리트 시험체의 철근 부식도 평가결과를 기초하여 180여개의 콘크리트 시험체를 새로이 제작하여 Half-Cell Test를 통한 Instant-Off Potential, Current Method를 통한 Corrosion Current, Chloride Content 및 시험 종료후 시험체를 파쇄하여 부식된 철근의 무게측정 등을 통하여 철근부식의 거동 및 부식을 예측 · 평가하고 이를 통한 부식방지기법을 개발하고자 한다.

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