- Technical paper -

EXPERIMENTAL INVESTIGATION ON CHLORIDE-INDUCED CORROSION IN POST-TENSIONED CONCRETE BEAMS

Ha Minh[*1], Hiroshi Mutsuyoshi[*2], Youichi Konno[*3] and Kyoji Niitani[*4]

ABSTRACT: An experimental program was carried out to investigate the behavior of post-tensioned concrete (hereafter PC) beams under severe condition of environment. To simulate deterioration of PC beams in a short period, an accelerated corrosion testing (hereafter ACT) method was adopted in this study. A series of accelerated corrosion tests were carried out to evaluate the influence of various parameters on corrosion of sheath and prestressing steel. Further, loading tests were conducted to investigate the mechanical behavior of PC beams deteriorated by corrosion. Results of experiments show that corrosion of sheath and prestressing steel has significant influence on load carrying capacity of PC beams.
KEYWORDS: accelerated corrosion test, chloride ion, corrosion, grout, post-tensioned concrete beams, prestressing steel, sheath

1. INTRODUCTION

Nowadays, deterioration of existing concrete structures has become a serious problem all over the world. The cost of repairing or replacing deteriorated structures has become a major liability for highway agencies, estimated to be more than $20 billion and to be increasing at $500 million per year in USA [1]. **Fig.1** [2] shows the deterioration of prestressing tendons. The primary cause of this deterioration (cracking, delamination, and spalling) is the corrosion of internal reinforcing bars and prestressing steel due to chloride attack, as this bridge is located in a coastal area and always exposed to seawater. In Japan, the major factor causing deterioration of PC bridges is chloride attack followed by poor grout condition. So far, very few studies have been conducted on corrosion of sheath and prestressing steel. Therefore, a clear understanding of the influence of chloride ion in grout on corrosion process has not yet been clarified. Further, the real behavior of PC beams deteriorated by corrosion is still far from being well understood. The objectives of this study are to investigate mechanical behavior of PC beams deteriorated by corrosion and to clarify the influence of chloride ion on corrosion of sheath and prestressing steel.

Fig.1 Deterioration of prestressing tendons [2]

*1 Graduate School of Science and Engineering, Saitama University, Ph. D Student, Member of JCI
*2 Department of Civil and Environmental Engineering, Saitama University, Professor, Member of JCI
*3 Graduate School of Science and Engineering, Saitama University, Member of JCI
*4 Oriental Construction Corporation, Tokyo, Japan, Member of JCI

2. EXPERIMENTAL PROGRAM

2.1 DETAILS OF SPECIMENS AND TEST VARIABLES

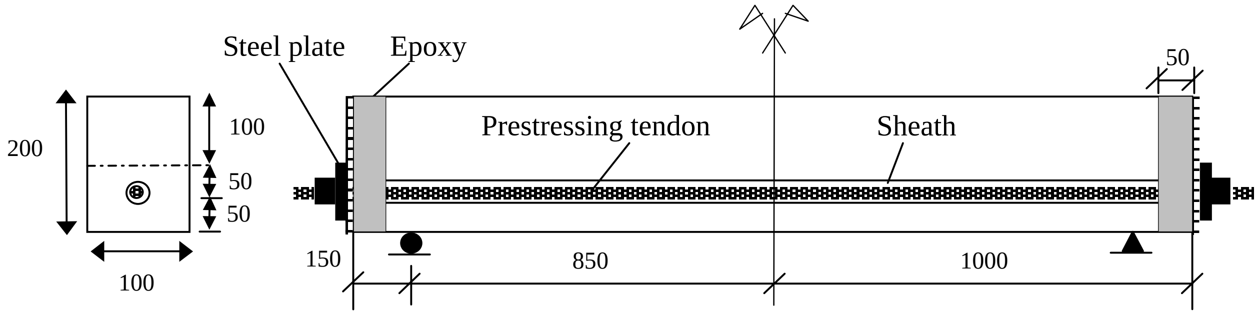

Fig. 2 Details of test beams (For series -A and series-C) (mm)

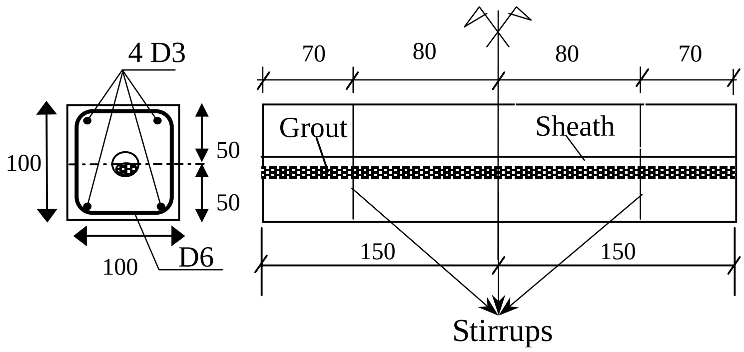

Fig. 3 Details of test beams (For series-S) (mm)

Three series of specimens (including series-A, series-C and series-S) were tested in this study. The cross section of all beams (except series-S) was 100 x 200 mm, as shown in **Fig. 2**. The length of these beams was 2000 mm. All the beams were cast in the laboratory using ready mixed concrete, having high early strength Portland cement with a maximum aggregate size of 20 mm and slump in the range of 100-140 mm. The average compressive strength of concrete was 40 MPa. The prestressing tendons used for the test specimen were of type SWPR7A with a diameter of 9.3 mm, having seven strands and the tensile strength was 1720 MPa. All the specimens were prestressed with 53.3 kN force in tendon. This force corresponds to approximately 60% of the ultimate tensile strength of tendon. After the tendon was stressed, it was anchored through the use of steel plate and wedge type anchorage at each end of the specimen. To avoid corrosion of steel plate, the ending 50 mm range of the specimen was coated with epoxy resin and a rubber pad was provided between the anchorage and the surface of concrete. After the tendon was stressed and anchored, grout (with W/C = 45%) was injected into the sheath.

For the specimens of series-S, the cross section was 100 x 100 mm and the length was 300 mm. All the specimens were provided with 4-D3 (deformed bar with diameter of 3 mm) longitudinal bars and 3-D6 (deformed bar with diameter of 6 mm) stirrups, as shown in **Fig.3.** In this experiment, electrical-resistance strain gages with 2 mm length were used for the measurement of strains in stirrups. To avoid the corrosion, the longitudinal bars and stirrups were coated with epoxy resin. Similar to the series-A, the average compressive strength of concrete was 40 MPa. No prestressing steel was used in this series. For bonded beams, grout (with W/C = 45%) was applied into the sheath until the desired depth of grout was gained.

Beam A1 was considered as the control beam. Chloride ions with 3 kg/m^3 were mixed in the concrete for all beams (except control beam). The purpose of applying chloride ions is to accelerate the corrosion process. For the beams of series-A, electric current was supplied for 2 weeks, 3 weeks, 4 weeks and 5 weeks for the beams A2, A3, A4 and A5 respectively. The purpose is to investigate the behavior of post-tensioned concrete beams in severe corrosive environment and to assess the weight loss of prestressing steel due to corrosion. For the beams of series-C, the chloride ions with 0.02%, 0.1%, and 0.2% by weight of Portland cement were mixed in the grout for the beams C1, C2 and C3 respectively.

The purpose is to evaluate the influence of chloride ions in the grout on corrosion of sheath and prestressing steel. For the beams of series-S without prestressing steel, the desired depth of grout was changed from 0% (un-bonded) for the beam S1 to 33% for the beam S2, 66% for the beam S3 and 100% for the beam S4. The purpose is to evaluate the influence of poor grout condition on corrosion of sheath. The stirrups were applied for this series and the strains developed in stirrups were measured to investigate radial pressure in the surrounding grout and concrete during corrosion process. **Table 1** shows the details of the specimens and the test variables for all beams.

Table 1. Details of specimens and test variables

No.	Name of beams	Applied current time (weeks)	Level of grout (%)	Diameter of sheaths (mm)	Applied Cl^- to concrete (kg/m^3)	Applied Cl^- to grout (%)
A1	G100-P60	0	100	20	0	0
A2	G100-P60-T2	2	100	20	3	0
A3	G100-P60-T3	3				
A4	G100-P60-T4	4				
A5	G100-P60-T5	5				
C1	G100-P60-Cl1	2	100	20	3	0.02%
C2	G100-P60-Cl2					0.1%
C3	G100-P60-Cl3					0.2%
S1	G0-S: Sheath only	0.5	0	20	3	0
S2	G33-S: Sheath only		33			
S3	G66-S: Sheath only		66			
S4	G100-S: Sheath only		100			

Where,

P60 = fpe/fpu = 60%; fpe: effective prestress; fpu: ultimate tensile strength of tendons
G0: un-bonded; G33, G66, G100: grout-filling level (in depth) of 33%, 66%, 100% respectively
Cl1, Cl2, Cl3: applied chloride ions with 0.02%, 0.1%, and 0.2% by weight of Portland cement
T2, T3, T4, T5: applied current time of 2 weeks, 3 weeks, 4 weeks and 5 weeks respectively

2.2 ACCELERATED CORROSION TEST

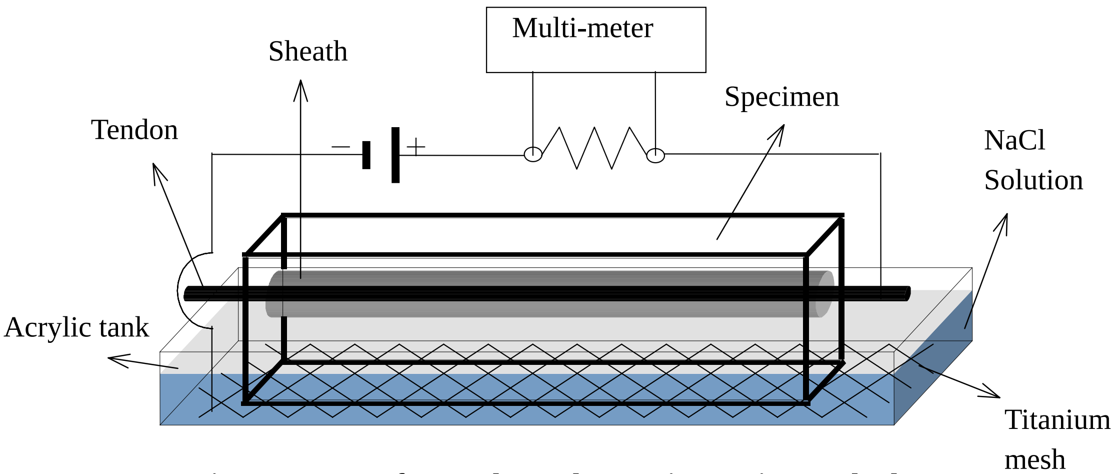

Fig.4 Test setup for accelerated corrosion testing method

To simulate the deterioration of PC beams in a short duration, ACT method was adopted. To have galvanic accelerated corrosion, the specimen was reversed and immersed into an acrylic tank with 5% sodium chloride solution that acts as an electrolyte. In this method, the prestressing steel of the specimen was made anode while titanium mesh in the bottom of acrylic tank was used as cathode. The test setup using ACT method is shown in **Fig.4**. The current was supplied through a current supplier to accelerate the corrosion process. For the beams of series-A and series-C, the current supplier had one end connected to the prestressing steel in the specimen and the other connected to the titanium mesh. For the beams of series-S, the current supplier had one end connected to the sheath in the specimen and the other connected to the titanium mesh. The electric current was kept constant at 0.7 A throughout the test. All the accelerated corrosion tests were carried out in the controlled room with temperature of 20°C and humidity of 60%. Crack pattern, crack width and tendon stress were measured during the tests.

2.3 LOADING TEST

After finishing accelerated corrosion tests, the beams of series-A and series-C were tested under four-point loading over the span of 1700 mm. Load was applied monotonically to the test beams until failure. The strains, deflection and applied load were recorded. Crack initiation and propagation were monitored by visual inspection during the tests.

3. RESULTS OF EXPERIMENTS AND DISCUSSION

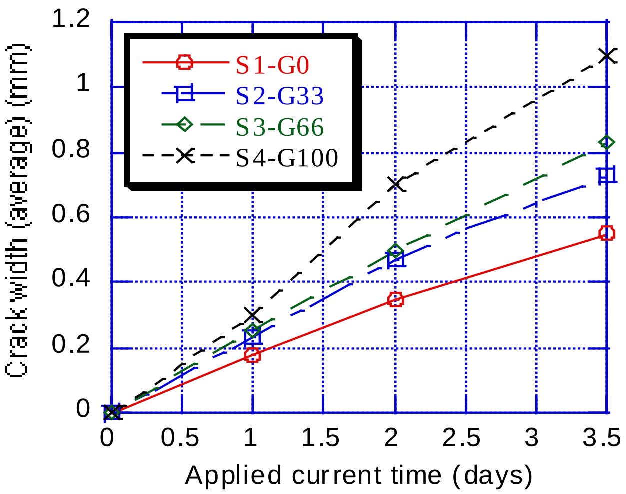

Fig. 5 Average crack width (Beam series-S)

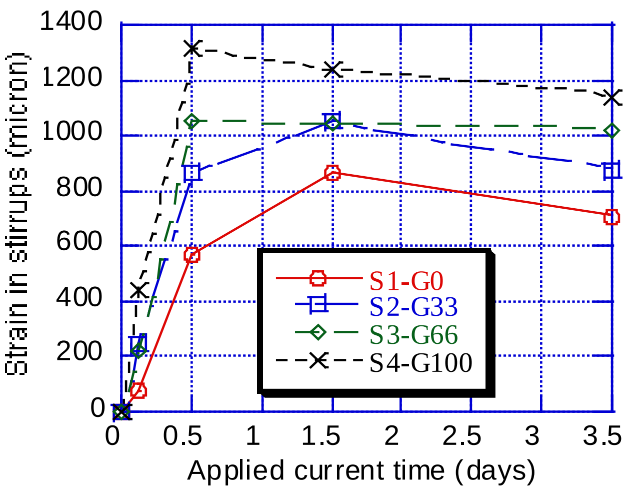

Fig. 6 Strain of stirrups (Beam series-S)

For the beams of series-S, cracks occurred in all the beams during accelerated corrosion test. It is confirmed that corrosion of sheath can cause the cracks of test beams. **Fig.5** shows the average crack width and **Fig.6** shows the strains of stirrups and applied current time relationship for this series. It shows that the crack width of the beams and strains developed in stirrups increase with the increasing grout-filling level. When the sheath corroded, the volume of the corrosion product became 2.5 to 3 times of the original volume of the sheath. Due to the increase in the volume, radial pressure was developed in the surrounding grout and concrete resulting cracks in concrete. It is confirmed that the new testing method presented in this study is effective to investigate the behavior of test beams during accelerated corrosion test.

Fig. 7 shows the crack patterns for the beams A2 and A5 due to corrosion process. During accelerated corrosion test, cracks occurred and propagated parallel to the longitudinal axis of the beams. **Fig.8** shows the relationship between average crack width and applied current time for the beams of series-A. From this figure, it is found that the crack width of test beams increases with the increase of applied current time. **Fig.9** shows the average crack width for the beams of series-C. This figure shows that chloride ion in the grout has almost no effect on corrosion cracking. The results of loading test and weight loss of prestressing tendons are shown in **Table 2**. Splitting cracks occurred along the longitudinal bars for all beams (except the control beam) during loading test and crushing of concrete occurred finally in the compression zone. All the test beams failed at lower load as compared to the control beam. It is confirmed that the corrosion of sheath and prestressing steel causes the reduction in the load carrying capacity of post-tensioned concrete beams. The beam C2 and C3 failed at almost the same load level. It shows that there is almost no effect of chloride ion mixed in the grout. **Fig. 10** shows the load-displacement relationship for the beams of series-A. It shows that the load carrying capacity reduces with the increase in applied current time. The maximum reduction in the load carrying capacity is 91% and the percentage of weight loss of prestressing tendon is 31% for the beam A5 as compared to the control beam A1. It is confirmed that the weight loss of prestressing tendon increases with the increase in applied current time.

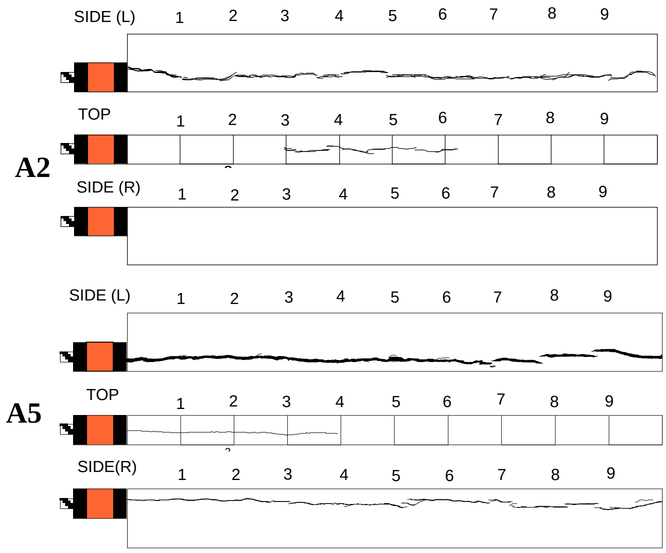

Fig. 7 Crack patterns (Beam A2 and A5)

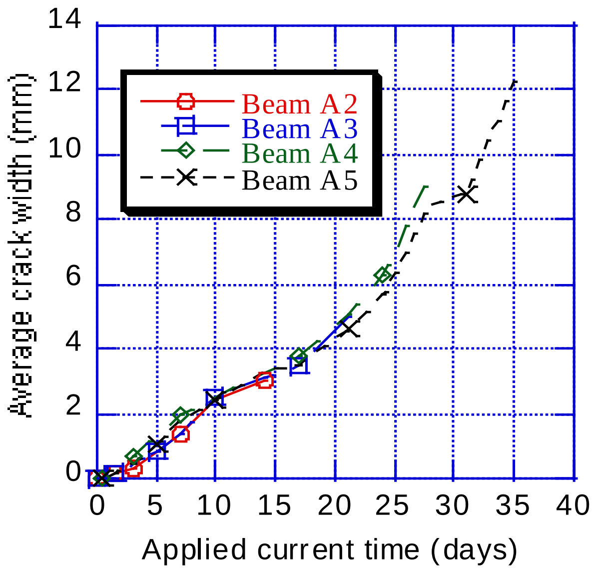

Fig. 8 Average crack width (Series-A)

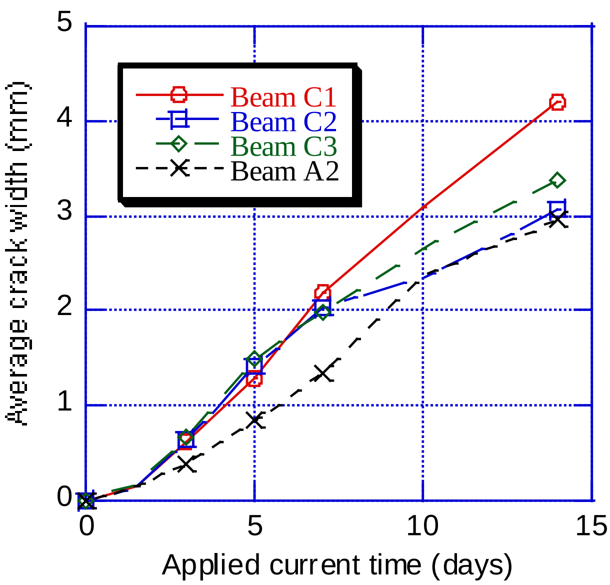

Fig. 9 Average crack width (Beam series-C)

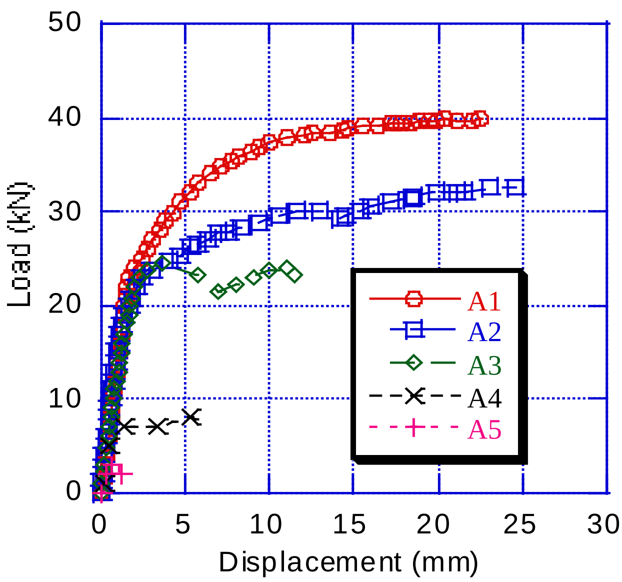

Fig. 10 Load-displacement relationship (Series-A)

Table 2. Results of loading test and weight loss of prestressing steel

No.	Name of beams	Exp. failure load (kN)	Relative strength	Weight loss	
				(g / 2m)	(%)
A1	G100-P60	39.8	1.0	0	0
A2	G100-P60-T2	32.5	0.82	8.2	1.03
A3	G100-P60-T3	24.5	0.62	27.6	3.47
A4	G100-P60-T4	8.0	0.20	105.9	13.32
A5	G100-P60-T5	3.7	0.09	245.2	30.84
C1	G100-P60-Cl1	30.2	0.76	13.4	1.68
C2	G100-P60-Cl2	27.0	0.68	0	0
C3	G100-P60-Cl3	27.3	0.69	0	0

4. CONCLUSIONS

From the results of experiments, the following conclusions can be drawn.

1. Corrosion of sheath and prestressing steel causes the reduction in the load carrying capacity of post-tensioned concrete beams.
2. Even without prestressing steel, corrosion of sheath can cause the cracks of test beams. The crack width of test beams increases with the increasing grout-filling level in the sheath.
3. Chloride ion in the grout has almost no effect on corrosion cracking and load carrying capacity of test beams.
4. The load carrying capacity of the test beams reduces with the increase in applied current time.
5. The weight loss of prestressing tendon increases with the increasing applied current time, which is due to the acceleration of corrosion process.
6. It is confirmed that the experimental methodology presented in this study is very effective to investigate the behavior of post-tensioned concrete beams deteriorated by corrosion.

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