コンクリート工学年次論文集, Vol.25, No.1, 2003

論文 EXPERIMENTS ON THE BEHAVIOR OF POST-TENSIONED CONCRETE BEAMS DETERIORATED BY CORROSION

Ha MINH*[1], Hiroshi MUTSUYOSHI*[2], Hirotsugu TANIGUCHI*[3]
and Kyoji NIITANI*[4]

ABSTRACT: Corrosion of prestressing steel is one of the major causes of serious degradation of prestressed concrete (hereafter PC) structures. In this study, a series of accelerated corrosion tests was carried out to evaluate the influence of various parameters on corrosion of the prestressing steel. Loading tests were also conducted to investigate the behavior of post-tensioned concrete beams deteriorated by corrosion of prestressing steel.

KEYWORDS: accelerated corrosion test, corrosion, grout, post-tensioned concrete beams, prestressing steel

1. INTRODUCTION

Deterioration of existing concrete structures has become a serious problem today 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]. The primary cause of this deterioration (cracking, delamination, and spalling) is the corrosion of internal reinforcing bars or prestressing steel due to chloride attack. Many bridges have been built in coastal areas and are exposed to seawater. Although PC members are generally built with high strength concrete under better quality control, they are subject to the same effects of corrosion as conventional reinforced concrete. However, because of the high stresses in the prestressing steel, the corrosion process is accelerated. Even small corrosion pits could cause a tendon to fracture. This is a serious problem as PC members rely on the high tensile strength of the tendons to resist applied loads.

There were three publicized collapses of European post-tensioned structures [2]. The three confirmed collapses all involved internally post-tensioned bridges and the collapses occurred without warning. These collapses were the Bickton Meadows bridge and the Ynys-y-Gwas bridge, both in UK; and a bridge over the River Schelde in Belgium. For PC structures, quality of grout in sheaths is a very important factor for the life and durability of post-tensioned PC structures. Recently, construction of post-tensioned PC structures with grouting has been forbidden by the Japan Highway Public Corporation, which governs most of the highway structures in Japan because bad quality of grouting after construction has been found in many bridges that were constructed in the boom era. From the results of an investigation conducted on 120 PC bridges in Japan [3], it is seen that the major factor causing deterioration of PC bridges is chloride attack followed by bad grout condition. Therefore the problem of corrosion of prestressing steel becomes very critical and should be considered seriously.

The objectives of this paper are to make clear the influence of grout condition on corrosion of the sheaths and prestressing steel and to investigate the behavior of post-tensioned concrete beams deteriorated by corrosion of prestressing steel.

2. EXPERIMENTAL PROGRAM

2.1 DETAILS OF SPECIMENS AND TEST VARIABLES

---

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

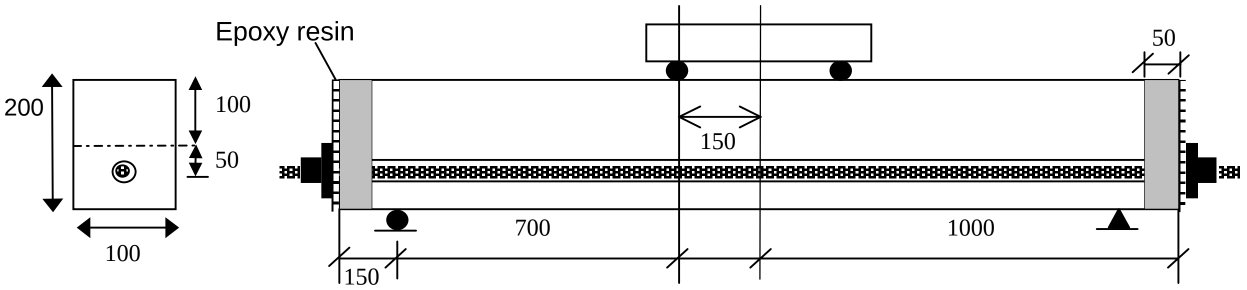

Fig. 1 Details of test beams (mm)

Nine PC beams were tested in this study. The cross section of all beams was 100 x 200 mm, as shown in **Fig. 1**. The length of the 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 tendons were stressed, they were 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 was provided between the anchorage and the surface of concrete. For un-bonded beams, a copperplate was provided in the center of the tendon so as to act as a connection between the tendon and the sheath. For bonded beams, after the tendons were stressed and anchored, grout was injected into the tendon ducts until the designed level of grout was gained. **Table 1** shows the details of the test specimens and the test variables.

Table 1. Details of specimens and test variables

No.	Name of beams	Applied current	Level of grout (%)	Existence of water in the duct	fpe/fpu (%)	Applied sodium chloride (NaCl)
B1	Non-current	No	100		60	No
B2	Non-chloride	Yes	100		60	No
B3	G0-P60	Yes	0	No	60	Yes
B4	G33-P60	Yes	33	No	60	Yes
B5	G66-P60	Yes	66	No	60	Yes
B6	G100-P60	Yes	100		60	Yes
B7	G0-W-P60	Yes	0	Yes	60	Yes
B8	G33-W-P60	Yes	33	Yes	60	Yes
B9	G66-W-P60	Yes	66	Yes	60	Yes

Where,
fpe: effective prestress
fpu: ultimate tensile strength of tendons
G0: unbond
G33, G66, G100: grout-filling level of 33%, 66%, 100% respectively
W: existence of water in the duct.

Beam B1 and B2 were tested as control beams. The chloride ions with the volumetric rate of 3 kg/m^3 were mixed in the concrete for the beams B3 to B9. The purpose of applying chloride ions is to accelerate the corrosion propagation process. The level of injected grout was changed from 0% (un-bond) for the beam B3 to 100% for the beam B6 to evaluate the influence of the grout condition on corrosion of the prestressing steel. The water was filled in the ducts for the beams B7 to B9 to investigate the influence of water in the duct on corrosion process.

2.2 ACCELERATED CORROSION TEST

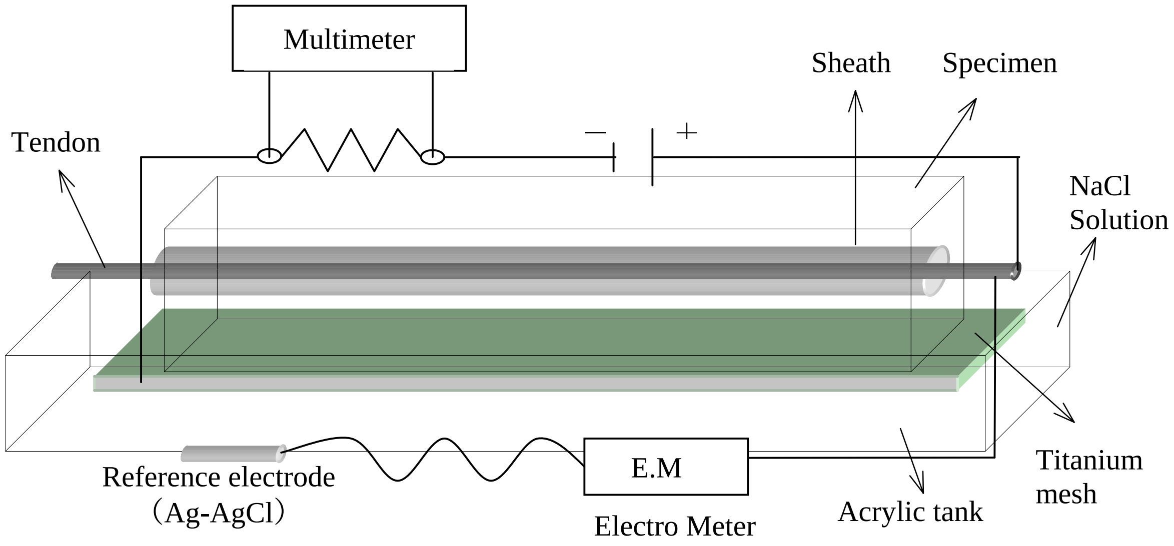

Fig.2 Test setup for accelerated corrosion testing method

To simulate the deterioration of PC beams in a short time, accelerated corrosion testing method (hereafter ACTM) was adopted. To have galvanic accelerated corrosion, the specimens were immersed upside-down into an acrylic tank with 5% sodium chloride (NaCl) solution that acts as an electrolyte. In this method, the prestressing steel of the specimen that had to be corroded was made anode and titanium mesh in the bottom of acrylic tank was used as cathode. The test setup using ACTM is shown in **Fig.2**. The current was then supplied through a current supplier to accelerate the corrosion process. The current supplier had one end connected to the prestressing steel in the specimen and the other connected to the titanium mesh. The electric current was kept constant of 0.7 A in all tests. All the accelerated corrosion tests were carried out in the standard room with temperature of 20°C and humidity of 60%.

The silver-silver chloride (Ag-AgCl) electrode was used as a reference electrode. Corrosion potential was measured from the reference electrode at nineteen different locations that were equally distributed in every 10 cm along the beam. **Table 2** shows the types of reference electrode and corrosion potential (vs. CSE: copper-copper sulphate electrode). According to JSCE-E 601 - 2000, if the corrosion potential is more positive than –250 mV CSE, there is no steel corrosion occurring in the area at the time of measurement. If the corrosion potential is in the range of –250 to –350 mV CSE, the point rust has occurred on the steel surface. If the corrosion potential is in the range of –350 mV to –450 mV CSE, the rust is spreading to the steel surface. If the corrosion potential is more negative than –450 mV CSE and continues, the rusts continuously develop and expand and finally cause the deficiency of the section. Corrosion potential was recorded by hand at 0.125 day, 0.5 day, 1.5 day and 7 days of applied electric current of 0.7 A. Crack pattern, crack width and tendon stress were also measured at each level.

Table 2. Type of reference electrode and corrosion potential (vs. CSE)

Type of reference electrode	Chemical formula	Corrosion potential (vs. CSE) t: Temperature when measuring (℃)
Copper-copper sulphate electrode (CSE)	$Cu\text{-}CuSO_4$	$0-0.9\times(t-25^{\circ}C)$
Silver-silver chloride electrode (SCE)	Ag-AgCl	$-91-0.6\times(t-25^{\circ}C)$

2.3 LOADING TEST

After finishing accelerated corrosion tests, all the beams 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 at every load increment. Crack initiation and propagation were monitored by visual inspection during the tests.

3. RESULTS OF EXPERIMENTS AND DISCUSSION

Fig.3 Corrosion of prestressing steel (Beam B8)

Fig. 4 Failure of beam B7 (G0 -W- P60)

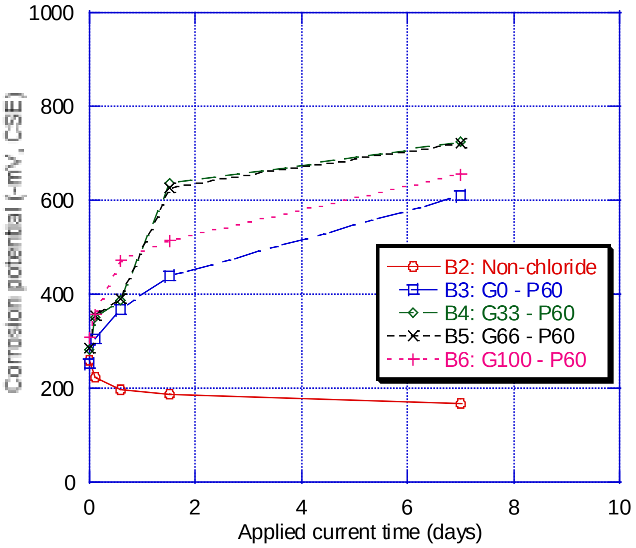

Fig. 5 Corrosion potential and applied current time (for beams B2 to B6)

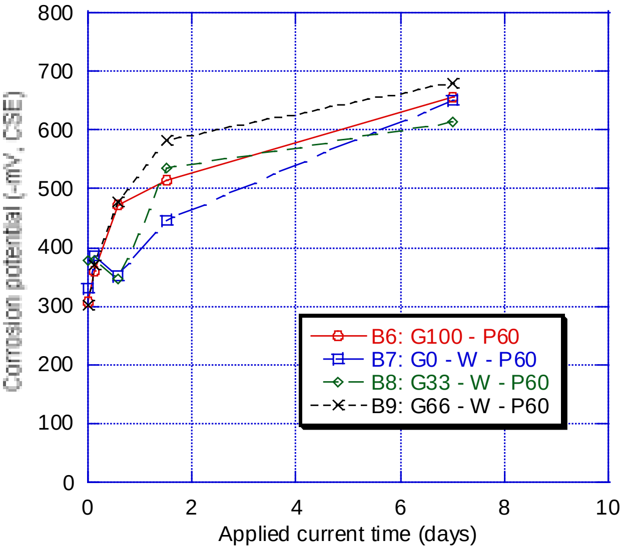

Fig. 6 Corrosion potential and applied current time (for beams B6 to B9)

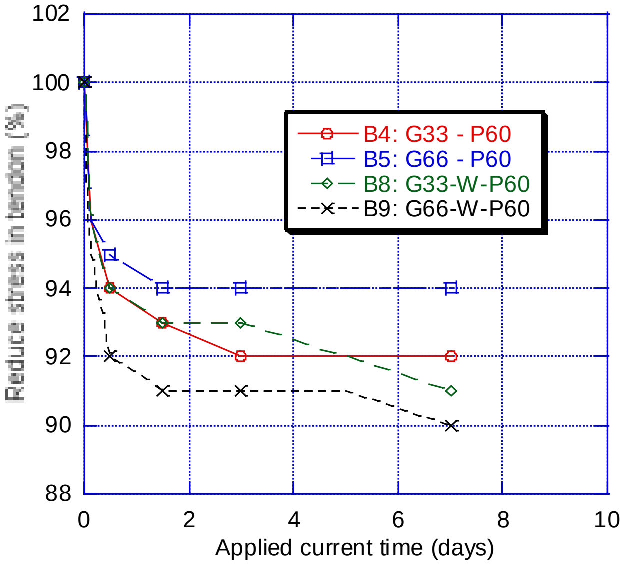

Fig. 7 Reduced stress in tendon - applied current time relationship

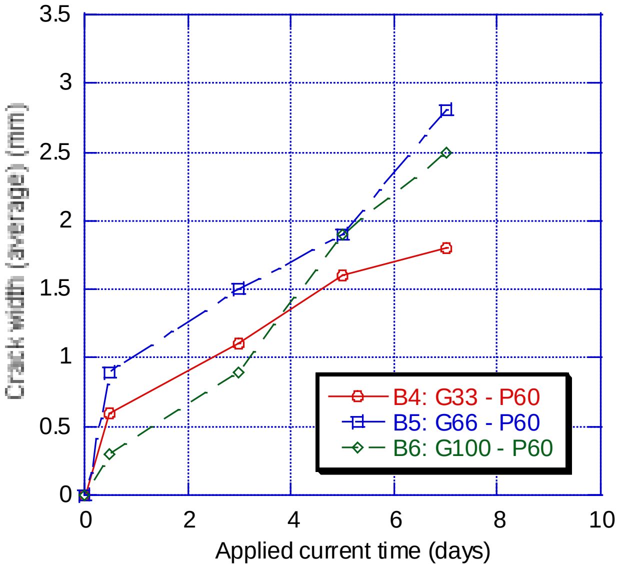

Fig. 8 Average of crack width - applied current time relationship

Table 3. Results of accelerated corrosion test

E: corrosion potential (-mV, CSE)

Applied current (day)	B2 (Non-chloride) E	B3 (G0-P60) E	B4 (G33-P60) E	B5 (G66-P60) E	B6 (G100-P60) E	B7 (G0-W-P60) E	B8 (G33-W-P60) E	B9 (G66-W-P60) E
0	260	254	282	284	308	330	379	301
0.125	222	305	351	354	359	386	379	371
0.5	197	366	386	391	473	352	347	478
1.5	187	439	635	626	514	446	536	582
7	169	610	724	723	657	650	614	679

Fig.3 shows the picture of corrosion of prestressing steel for the beam B8 (G33-W-P60) and **Fig.4** shows the failure of the beam B7 (G0-W-P60). **Table 3** shows the result of accelerated corrosion test. The relationships between corrosion potential and applied current time for all beams are shown in **Fig.5** and **Fig.6**. Corrosion of the sheaths and prestressing tendons occurred in all beams (except beam B2). The rust was observed in the sheaths and prestressing steel for all beams (except beam B2) and the measuring corrosion potentials for those beams were more negative than –450 mV CSE. No corrosion occurred in the sheath and prestressing tendon for the beam B2 because no sodium chloride solution was mixed in the concrete. It is confirmed that the experimental methodology presented in this study is very effective to predict the corrosion of the sheaths and prestressing steel. **Fig.7** shows the reduction of stress in tendon for the beams with and without applying water. The reductions of stress in tendons for the beams B8 and B9 (filled up water in the duct) were faster than those of the beams B4 and B5 (without water). It shows that the tendon stress reduces with the increase of water in the ducts, which might be due to the acceleration of corrosion process of prestressing steel. **Fig.8** shows the average of crack width for the beams B4, B5 and B6. This figure shows that the crack width of the beams increases with the increasing grout-filling level. When the sheaths and prestressing steel corroded, the volume of the corrosion product became 2.5 to 3 times of the original volume of steel. Due to the increase in the volume, radial pressure was developed in the surrounding grout and concrete resulting cracks in concrete. Therefore the crack width of the beams increases with the increasing grout-filling level in the sheaths.

The result of loading test is shown in **Table 4. Fig.9** and **Fig.10** show the load-displacement relationship for all test beams. All the beams failed in flexure and crushing of concrete occurred finally in the compression zone. The control beam B1 failed at the load of 40 kN. The beam B2 failed at almost the same load level since no corrosion occurred in the sheaths and prestressing steel of this beam. The failure load of the beam B6 (G100-P60) was lower than that of the control beam B1. It is confirmed that the corrosion of prestressing steel caused the decrease of loading capacity of post-tensioned concrete beams. The failure loads of the beams B7 (G0-W-P60), B8 (G33-W-P60), B9 (G66-W-P60) were lower than those of the beams B3 (G0-P60), B4 (G33-P60), B5 (G66-P60) respectively. It shows that the water filled in the sheaths caused the reduction of loading capacity of post-tensioned concrete beams.

Table 4. Results of loading test

No.	Name of beams	Exp. failure load (kN)	Exp. failure mode	Ratio of reduce load capacity
B1	Non-current	40.0	flexure	1.0
B2	Non-chloride	39.3	flexure	0.98
B3	G0-P60	33.6	flexure	0.84
B4	G33-P60	34.4	flexure	0.86
B5	G66-P60	36.7	flexure	0.92
B6	G100-P60	31.3	flexure	0.78
B7	G0-W-P60	28.0	flexure	0.70
B8	G33-W-P60	32.2	flexure	0.81
B9	G66-W-P60	29.8	flexure	0.75

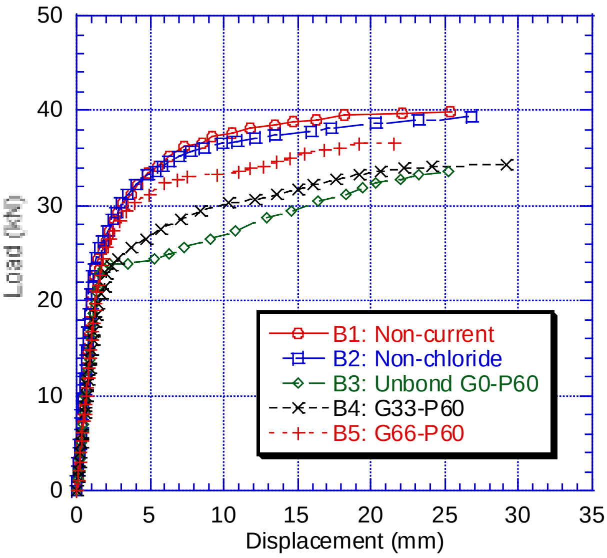

Fig. 9 Load-displacement (B1-B5)

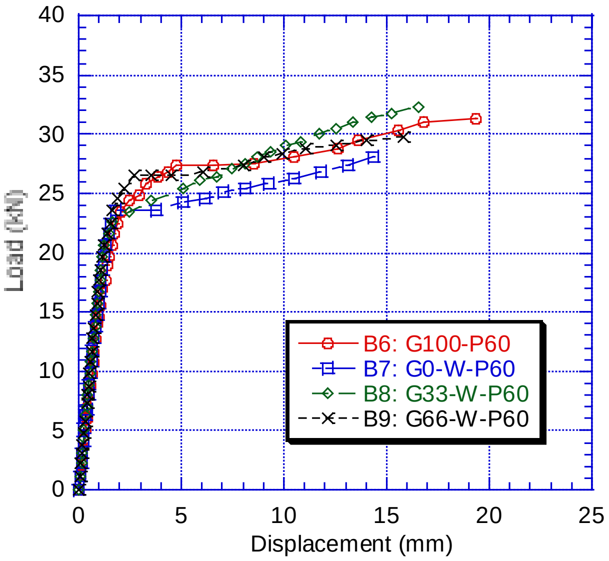

Fig. 10 Load-displacement (B6-B9)

4. CONCLUSIONS

Experimental study was conducted to make clear the influence of grout condition on corrosion of the sheaths and prestressing steel and to investigate the behavior of post-tensioned concrete beams deteriorated by corrosion. From the results of experiments, the following conclusions can be drawn.

1. It is confirmed that the corrosion of the prestressing steel caused the reduction of loading capacity of post-tensioned concrete beams.
2. The crack width of test beams increases with the increasing grout-filling level in the sheaths.
3. The water filled in the sheaths can cause the reduction of loading capacity of post-tensioned concrete beams.
4. 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 of prestressing steel.

ACKNOWLEDGMENT

The authors would like to express their deep appreciation to Oriental Construction Corporation, Japan for their technical and material support in the experiment. Sincere thanks are also due to Mr. Youichi Konno, graduate student of Structural Material Lab, Saitama University for his help in carrying out the experiment.

REFERENCES

1. Smith, J. L. and Virmani Y. P., “Material and Methods for Corrosion Control of Reinforced and Prestressed Concrete Structures in New Construction”, Report No. FHWA-RD-00-081, Federal Highway Administration, USA, 2000, pp. 1-78
2. Schokker, A. J., Breen, J. E., and Kreger, M. E., “Grouts for Bonded Post-Tensioning in Corrosive Environments”, ACI Materials Journal, V.98, No.4, 2001, pp. 296-304
3. Mutsuyoshi, H., “Present Situation of Durability of Post-Tensioned PC Bridges in Japan”, Proceedings of Workshop on Durability of Post-tensioning Tendons, fib, Belgium, 2001, pp. 75-88
4. Yoon, S., Wang, K., Weiss, W. J, Shah, S. P., “Interaction between Loading, Corrosion, and Serviceability of Reinforced Concrete”, ACI Materials Journal, V.97, No.6, 2000, pp. 637-644
5. Roberge, P. R., “Handbook of Corrosion Engineering”, McGraw Hill Companies Inc., USA, 2000, pp. 154-187