- Technical Paper -

# STUDY ON CHLORIDE-INDUCED CORROSION IN POST-TENSIONED CONCRETE BEAMS WITH INSUFFICIENT GROUT CONDITION

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# ABSTRACT

An experimental program was carried out to clarify the effect of chloride-induced corrosion on post-tensioned concrete (PC) beams under different grout conditions using accelerated corrosion testing method (ACTM). The influence of different quantities of grout in parabolic segment of sheath on prestressing tendon corrosion was clarified. The radial pressure surrounding the tendon during corrosion process was also investigated. After a period of accelerated corrosion, the mechanical behavior of the deteriorated PC beams was clarified through loading test. Keywords: accelerated corrosion test, chloride-induced corrosion, insufficient grout, post-tensioned concrete beams, prestressing tendon, steel sheath

### **1. INTRODUCTION**

In general, properly designed and constructed PC structures are highly durable. Prestressing tendons are protected against corrosion by filling the duct with cement grout. The duct profiles in actual PC bridges can be described as a series of parabolic segments with concave segments in the span and convex segments over the support. Because of a number of factors, however, the deterioration of prestressing tendons and reinforcing bars in PC bridges has become a serious problem in recent years throughout the world. There have been three reports of internal post-tensioned bridges collapsing without warning in the U.K and Belgium [1]. The main reason for these collapses was deterioration of prestressing tendons.

In Japan, the major factor leading to deterioration of PC bridges is chloride attack (as a result of using sea sand, airborne salt from the sea, or the use of deicing chemicals), while the second-most important is insufficient grouting. This means that the problem of prestressing steel corrosion arising from chloride attack and insufficient grout are critical issues and must be taken very seriously. So far, the deterioration of RC structures under chloride attack has been studied by many researchers and its mechanism is being clarified. In contrast, the mechanism of PC bridges deterioration under the influence of chloride ions has hardly been studied. Further, the influence of insufficient grouting on the corrosion process has not yet been clarified at all. The objectives of this study are to make clear the influence of insufficient grout condition in parabolic steel sheath on prestressing tendon corrosion and to clarify the radial pressure surrounding the tendon during the corrosion process. The mechanical behavior of PC beams after deterioration by chloride-induced corrosion was also investigated.

## 2. EXPERIMENTAL PROGRAM

2.1 Details of Specimens and Test Variables

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Fig. 1 Details of test beams (series -A) (mm)





Two sets of tests, series-A and series-B, were conducted. The purpose of series-A is to make clear the influence of insufficient grouting in parabolic steel sheath on PC beam corrosion, while series-B is designed to clarify the radial pressure surrounding the tendon during the corrosion process. The details of the test specimens used for series-A is shown in Fig.1. All the beams were provided with 4-D6 (deformed bars 6 mm in diameter) longitudinal bars and 7-D6 stirrups at 200 mm center to center spacing. To avoid the corrosion, the longitudinal bars and stirrups were coated with epoxy resin. A spiral steel sheath with a diameter of 20 mm was used for all specimens. All the beams were cast in the laboratory using 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 were of the strand type with a diameter of 9.3 mm and designated SWPR7A in Japan. Their tensile strength was 1720 MPa. All specimens were prestressed with 53.3 kN force corresponding to approximately 60% of the tensile strength of the tendon. After stressing, the tendon was anchored using wedge-type anchorages at each end of the specimen through the steel plate. To avoid corrosion of the steel plate, the area up to 50 mm from each end of the specimen was coated with epoxy resin and a rubber pad was inserted between the steel plate and the specimen itself. After tendon stressing and anchoring, grout (W/C = 45%) was injected into the sheath.

The details of the test specimens used for series-B is shown in Fig.2. All the specimens were provided with 4-D3 (deformed bar 3 mm in diameter) longitudinal bars and 3-D6 stirrups. In this experiment, electrical-resistance strain gages with 2 mm length were used to measure strains of stirrups. Similar to the series-A, the longitudinal bars and stirrups were coated with epoxy resin and the average compressive strength of concrete was 40 MPa. After casting of series-B, spiral steel sheath was removed from the specimen so that only the tendon was used for the accelerated corrosion test. After removing the sheath, grout (W/C = 45%) was applied into the void space until the desired depth of grout was gained.

Table 1 lists the test specimens and the experimental variables. Beam A1 was the control specimen, while chloride ions at a concentration of 3 kg/m<sup>3</sup> were added to the concrete used for the other beams to accelerate corrosion. In series-A, the grout filling level was varied from 0% (A2) to 50% (A3), and 100% (A4) to clarify the influence of insufficient grout conditions in the parabolic sheath on PC beam corrosion. In series-B, the desired depth of grout was changed from 33% (B1) to 66% (B2) and 100% (B3) to evaluate the influence of insufficient grout conditions on corrosion of tendon. The stirrups were provided for this

No.	Accelerated time (weeks)	Level of grout (%)	Initial Cl <sup>-</sup> in concrete (kg/m <sup>3</sup> )	Remarks
A1	0	100	0	Control beam
A2		0		L0-P60
A3	4	50		L50-P60
A4		100	3	L100-P60
<b>B1</b>		33	5	G33: Tendon only
B2	0.5	66		G66: Tendon only
<b>B3</b>		100		G100: Tendon only

Table 1 Details of specimens and test variables

Where,

P60 = fpe/fpu = 60%; fpe: effective prestress; fpu: ultimate tensile strength of tendons.

L0: un-bonded, however grout was filled in the parabolic sheath with a length of 15cm in a horizontal direction from each end of the beam to the support.

L50: grout was filled in the parabolic sheath with a length of 47.5 cm in a horizontal direction from each end of the beam (the total length of grout from the support is equivalent to 50% of the beam span).

L100: perfect grouting

G0: un-bonded; G33, G66, G100: grout level (in depth direction) of 33%, 66%, 100%, respectively.



Fig. 3 Test setup for accelerated corrosion testing method (Series-A)

series and the strains developed in stirrups were measured to investigate radial pressure surrounding the tendon during the corrosion process.

## 2.2 Accelerated Corrosion Test

ACTM was adopted to simulate the long-term deterioration of PC beams in a short period. To induce galvanic accelerated corrosion, the specimen was immersed in an acrylic tank containing 5% sodium chloride solution as an electrolyte. The prestressing steel in the specimen acted as the anode, while titanium mesh positioned in the bottom of the tank was the cathode. An external direct current was applied by a current source. The test setup for ACTM is shown in Fig.3. The current was kept constant at 0.57 A for the beam series-A and 0.7 A for the beam series-B throughout the tests, which were carried out in a controlled environment at a temperature of 20°C and a relative humidity of 60%. Crack pattern and crack width were monitored during the tests.

### 2.3 Loading Tests

After accelerated corrosion for a certain period, each beam in series-A was tested under four-point loading over a span of 1300 mm. Loading was applied monotonically to the test beams up to failure. The strains, deflection, and applied load were measured. Crack initiation and propagation were also observed visually during the tests.

# 3. RESULTS OF EXPERIMENTS AND DISCUSSION

3.1 Influence of Insufficient Grout in Parabolic Sheath on Corrosion Cracking





For the series-A beams, cracks occurred in all beams during accelerated corrosion test. Crack occurred after 19 hours of current supply for the beams A3 and A4 while for the beam A2 crack occurred after 34 hours of accelerated corrosion. It means that the corrosion-induced crack in the grouted beam tended to occur earlier than that in un-bonded ones. Figure 4 shows the crack patterns of the beam A4 after two weeks of accelerated corrosion. The corrosion crack occurred and propagated along the tendon level during the corrosion process. During testing, crack width was measured at 8 different points, distributed at equal 20 cm intervals, along the beam. The relationship between average crack width at different points and accelerated time for beams A2, A3 and A4 are shown in Fig.5, Fig.6 and Fig.7, respectively. In beams A2 and A3, the crack width increased from the center to both ends of the specimen. The reason is due to the different lengths of the grout filled inside the parabolic sheath.



In beam A4, the crack width was almost the same in all points since grout was filled 100% for this specimen. The cracks widened with increasing time in all cases. However, a large quantity of the corrosion product came

out through the cracks near the center of parabolic sheath resulting in smaller crack width at this location as compared to the location near both ends of the beam.

# 3.2 Influence of Insufficient Grout in Parabolic Sheath on Reduction of Stress in Tendon

Figure 8 shows the reduction of stress in tendon for series-A beams. The reduction of stress in tendons for the un-bonded beam A2 (L0) was faster than that of the beams A3 (L50) and A4 (L100). That is, the tendon stress reduces with the decrease in the length of grout filling level inside the parabolic sheath. The reason is due to the acceleration of corrosion process of prestressing tendon in insufficiently grouted beams. The prestressing tendon in the un-bonded beam A2 corroded faster than that of the beams A3 and A4. The maximum reduction of tendon stress was 80% for the un-bonded beam A2. This confirmed that insufficient grout inside parabolic sheath has a significant influence on the reduction of tendon stress in PC beams.

# 3.3 Relationship between Corrosion Crack and Radial Pressure due to Tendon Corrosion

Figure 9 and 10 show the average crack width and strains in stirrups against accelerated time relationships for series-B beams. It shows that the crack width of the beams and strains developed in stirrups increase with the increase in grout filling level. As the tendon corrodes, the volume of corrosion products rises to 2.5 to 3 times the original tendon volume. This increase in volume generates radial expansive pressure on the surrounding concrete, causing cracks to occur. With more grout covering the tendon, the expansive pressure is greater. That is, the radial expansive pressure in an insufficiently grouted specimen is lower than that in a sufficiently grouted one because of the existence of voids in the sheath. This explains why the crack width increases with grout filling level inside the sheath. No corrosion crack occurred in the specimen B1 since the expansive pressure due to tendon corrosion was not sufficient to cause cracking.



3.4 Influence of Corrosion on Load-Carrying Capacity of PC Beams

The results of the loading tests for series-A beams are shown in Table 2, along

No.	Ultimate	Weight loss	
	failure	(g)	(%)
A1	94.0	0	0
A2	45.8	131.42	20.4
A3	43.0	126.25	19.6
A4	42.2	110.91	17.2

Table 2 Results of loading test and weight loss of prestressing tendon (Series-A)

with measurements of the percentage weight loss of prestressing tendons. Figure 11 shows the load-displacement relationships for the beams in series-A. All the beams failed in flexural mode and concrete crushing occurred near the loading point. There was severe corrosion and the prestressing tendons ruptured during corrosion process in all beams. Therefore only reinforcements were resisted the applied load. This explains why those beams with different grout condition failed at almost the same load level. The average reduction in the load-carrying capacity is more than 50% as compared to the control beam. This confirmed that corrosion of the prestressing tendon has a significant influence on the deterioration of load-carrying capacity in PC beams. The maximum prestressing tendon weight loss was 20% for the beam A2. The prestressing tendon weight loss was less in the sufficiently grouted beam than in the insufficiently grouted ones. This shows that the prestressing tendon is better protected if grout is filled sufficiently.

![](_page_5_Figure_3.jpeg)

#### 4. CONCLUSIONS

From the results of these experiments,

the following conclusions can be drawn:

1. Corrosion of prestressing tendon leads to a significant reduction in the load-carrying capacity of a PC beam. The average reduction in the load-carrying capacity is more than 50% for all test beams.

2. Corrosion-induced cracking tends to occur earlier in sufficiently grouted beams than in insufficiently grouted ones. As the level of grout in the sheath increases, the corrosion crack propagates faster along the prestressing tendon. The width of this corrosion-induced crack and radial pressure due to tendon corrosion also increases with the level of grout in the void. However, the prestressing tendon is better protected by sufficient grouting despite the greater width of the corrosion-induced crack. This demonstrates that grouting is an important factor related to prevention of prestressing tendon corrosion.

3. Insufficient grout inside the parabolic sheath has a significant influence on the reduction of tendon stress in PC beams.

4. It is confirmed that the experimental methodology presented in this study is a very effective means of investigating the behavior of PC beams as they deteriorate under the influence of chloride-induced corrosion.

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