- Technical Paper -

INFLUENCE OF GROUTING CONDITIONS ON DETERIORATION OF POST-TENSIONED PRESTRESSED CONCRETE BEAMS

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ABSTRACT

Chloride-induced corrosions of a sheath and a prestressing tendon in post-tensioned prestressed concrete (PC) beams are investigated under different grouting conditions. Two series PC beams were tested by the electrically accelerated corrosion. The first series of accelerated corrosion tests were performed to determine the influence of grouted ratios in a curved sheath on the corrosion of the sheath and the prestressing tendon. In the second series of tests, the relationship between corrosion crack and expansive pressure surrounding the sheath and tendon during the corrosion process was clarified.

Keywords: accelerated corrosion testing method, chloride-induced corrosion, grout, post-tensioned prestressed concrete beams, prestressing tendon, sheath

1. INTRODUCTION

PC structures properly designed and constructed generally have been considered highly durable because the prestressing tendons could be protected from corrosion by filling the duct with cement grout. In recent years, however, deterioration problems have been discovered in some existing PC bridges, raising serious concerns about the long-term durability of PC bridges. The major cause of deterioration in PC bridges is the corrosion of prestressing tendons, which affects structural performance in terms of serviceability and load-carrying capacity. Collapses of three internal post-tensioned bridges are reported without warning in the U.K and Belgium [1]. The main reason for these collapses was deterioration of the prestressing tendons. In Japan, the major cause of deterioration in PC bridges is corrosion due to chloride attack from airborne salt from the sea, the use of sea sand in the concrete, or the use of deicing chemicals. The second leading cause is insufficient grouting [2-3]. The prestressing steel corrosion caused by chloride attack and insufficient grouting is therefore a critical issue that must be taken very seriously.

Many researchers have studied corrosion of reinforced concrete (RC) structures under chloride attack, and its mechanism is being clarified. In contrast, few studies have investigated the influence of chloride ions on the corrosion of PC bridges. Further, the influence of grouting conditions inside a sheath on the corrosion process has not yet been clarified. The objectives of this study are to clarify the influence of grouted ratios in curved sheaths on corrosion of prestressing tendon and to investigate the relationship between corrosion crack and expansive pressure surrounding the sheath and prestressing tendon during the corrosion process. The influence of corrosion of the sheath and the prestressing tendon on the deterioration of the load-carrying capacity of PC beams was also clarified in this study.

2. EXPERIMENTAL PROGRAM

2.1 Details of Specimens and Test Variables

In order to clarify the process by which PC beams deteriorate due to corrosion, two series of PC beams, Series A and Series S, were subjected to electrically accelerated corrosion. Series A was employed to clarify the influence of the ratios of the grout filling in a curved sheath on the corrosion of the sheath and the prestressing tendon. In Series S, the relationship between corrosion crack and expansive pressure surrounding the sheath and prestressing tendon during the

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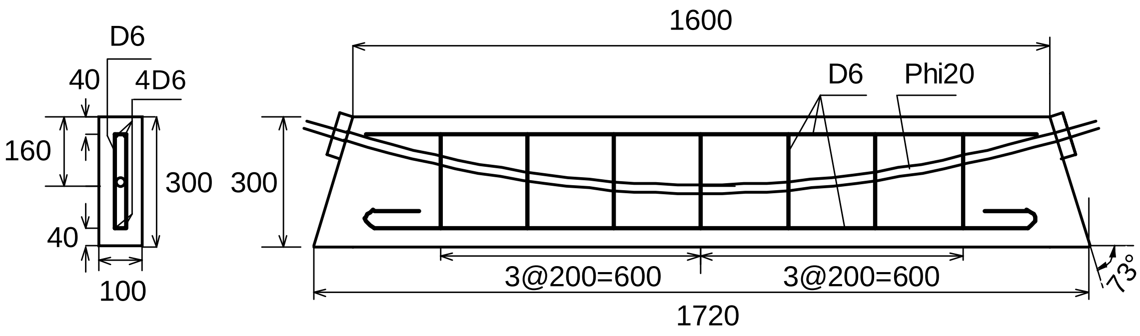


Fig. 1 Configuration of test beams (Series A) (mm)

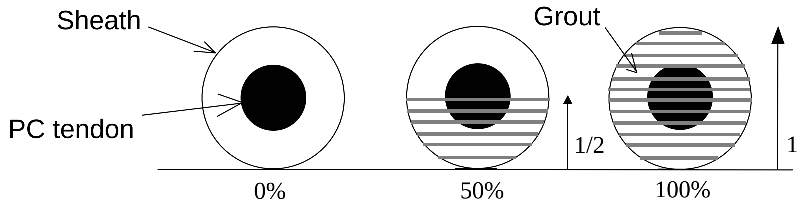
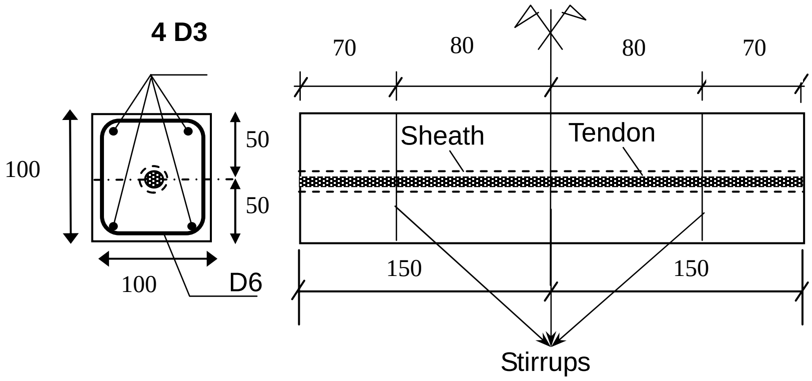


Fig. 2 Grouted ratios at center section of the sheath (Series A)



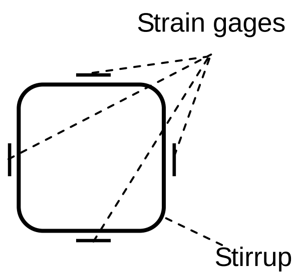


Fig. 3 Configuration of test beams (Series S)

Fig. 4 Locations of strain gages

corrosion process was investigated. The test variables were based on the grouting conditions of actual PC bridges. All of test beams were cast in a laboratory using high-early-strength Portland cement with a maximum aggregate size of 20 mm and a slump ranging from 100 to 140 mm. The design strength of concrete was specified as 40 MPa which is usually used for actual PC structures. Two types of sheaths were used in the test: curved for Series A, and straight for Series S. The prestressing tendon was of strand type with a diameter of 9.3 mm and designated as SWPR7A in Japan. Its tensile strength was 1720 MPa.

Figure 1 show the configuration of test beams of Series A. The beams of Series A were reinforced with 4-D6 (four deformed bars with a diameter of 6 mm) longitudinal bars and 7-D6 stirrups with center-to-center spacing of 200 mm. The longitudinal bars and stirrups were coated with epoxy resin to prevent corrosion. All of the test beams of Series A were prestressed with a 53.3 kN force, which corresponds to approximately 60% of the tensile strength of the tendon. After stressing, the tendon was anchored through the steel plate using wedge-type anchorages at each end of the test beam. To prevent corrosion of the steel plate, the area extending 50 mm from each end of the test beam was coated with epoxy resin and a rubber pad was inserted between the steel plate and the beam. After the tendon was stressed and anchored, grout was injected into the sheath. Table 1 lists the details of test specimens and the experimental variables for all beams. To accelerate the corrosion, sodium chloride of 3 kg/m^3 was added to concrete used for all beams except beam A0. Beam A0 was the control specimen of the Series A. The curved sheath of each beam of Series A was filled with different grouted ratios at the center section, as shown in Fig. 2, in order to clarify the influence of the grouting conditions on corrosion of the prestressing tendon. Other sections of the curved sheath were filled with full grouting. The grouted ratios at center section of the sheaths were varied

Table 1 Details of specimens and test variables

No.	Accelerated time (weeks)	Grouted ratios (%)	Initial Cl^- in concrete (kg/m^3)	Remarks
A0	0	100	0	Control beam
A1	2	0	3	G0-P60
A2		50		G50-P60
A3		100		G100-P60
A4	3	0		G0-P60
A5		50		G50-P60
A6		100		G100-P60
S1	0.5	0	3	G0-S
S2		33		G33-S
S3		66		G66-S
S4		100		G100-S
S5		33		G33-T
S6		66		G66-T
S7		100		G100-T

Note: Symbols for specimen identification:
P60 = fpe/fpu = 60%; fpe: effective prestress; fpu: ultimate tensile strength of tendons
G0, G33, G50, G66, G100: grouted ratios of 0%, 33%, 50%, 66%, 100% respectively
S: specimen with sheath only.
T: specimen with tendon only.

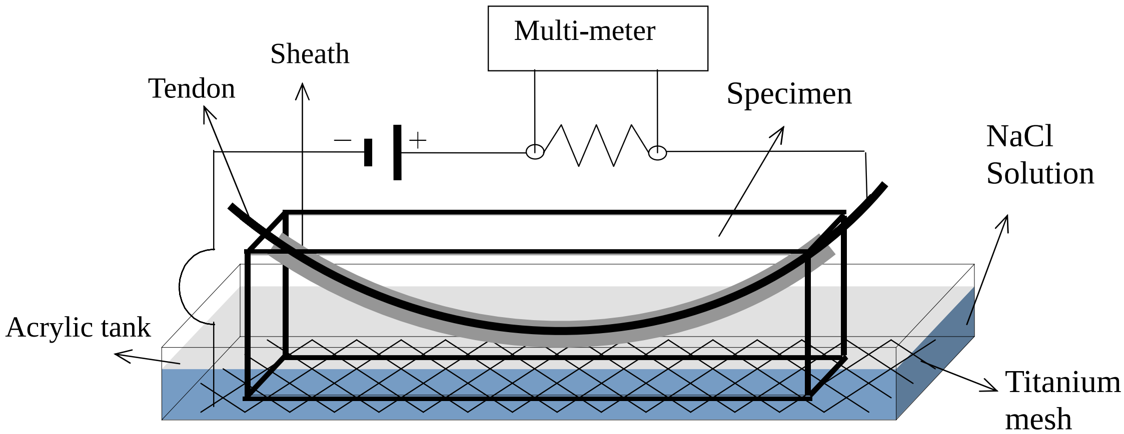


Fig. 5 Test setup for accelerated corrosion testing method (Series A)

as 0% (beams A1, A4), 50% (beams A2, A5), and 100% (beams A3, A6).

Figure 3 show the configuration of test specimens of Series S. All the specimens were provided with 4-D3 (deformed bar of 3 mm in diameter) longitudinal bars and 3-D6 (deformed bar of 6 mm in diameter) stirrups. In this experiment, electrical-resistance strain gages with 2 mm length were used to measure strains of stirrups. The purpose is to investigate expansive pressure surrounding the sheath and steel tendon during the corrosion process. Locations of strain gages are shown in Fig. 4. To avoid the corrosion, the longitudinal bars and stirrups were coated with epoxy resin. For the beams S1 to S4, no steel tendon was provided since the purpose is to investigate the relationship between corrosion crack and expansive pressure due to corrosion of the sheath only. Desired depth of grout was varied as 0% (S1), 33% (S2), 66% (S3) and 100% (S4) to evaluate the influence of grouted ratios on the corrosion of sheath. For the beams S5 to S7, steel tendon with a diameter of 9.3 mm was provided. After casting, however, spiral steel sheath was removed from those beams so that only the tendon was used for the accelerated corrosion test. The purpose is to investigate the relationship between corrosion crack and expansive pressure due to corrosion of tendon only. After removing the sheath, grout was applied until the desired depth of grout was gained. The grouted ratio was varied as 33% (S5), 66% (S6) and 100% (S7) to evaluate the influence of grouted ratios on the corrosion of steel tendon.

2.2 Accelerated Corrosion Test

In order to produce corrosion of the tendons in a short time, this study adopted the accelerated corrosion test method (ACTM). To induce galvanic accelerated corrosion, the test beam was immersed in an acrylic tank containing 5% sodium chloride solution as an electrolyte. The prestressing tendon in each specimen served as the anode, while a titanium mesh placed in the bottom of the tank served as the cathode. The test setup for ACTM is shown in Fig. 5. An external direct current was applied by a current source. The current source had one end connected to the prestressing tendon in the specimen and the other end to the titanium mesh. The current was kept constant 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 the specimens were subjected to ACTM for the specified period, beams in Series A were tested under four-point loading with a span of 1300 mm. Loading was applied monotonically up to final failure. The strains, deflection, and applied load were measured. Crack initiation and propagation were also visually monitored during the tests.

3. RESULTS OF EXPERIMENTS AND DISCUSSION

3.1 Influence of Grouted Ratios in Curved Sheath on Corrosion Cracking

Fig. 6 shows a typical crack pattern of series-A due to accelerated corrosion test. Cracks developed in all beams of series-A during ACTM. The corrosion-induced cracks develop and propagate along the curved sheaths. During the tests, the crack widths were measured at 8 points along the beam at the intervals of 20 cm. Relationships between the average crack-width at the mid-span of the beams and the accelerated period for all beams are shown in Fig. 7. The average crack width was calculated by averaging the detailed crack data obtained at point 4 and 5. Corrosion-induced cracks in the fully-grouted beam occur earlier than those in the insufficiently-grouted beams. The crack width increases as the grouted ratio inside the sheath increases. The reason will be explained in the following section.

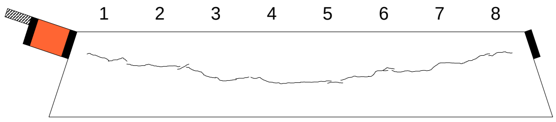


Fig. 6 Typical crack pattern of Series A due to accelerated corrosion test

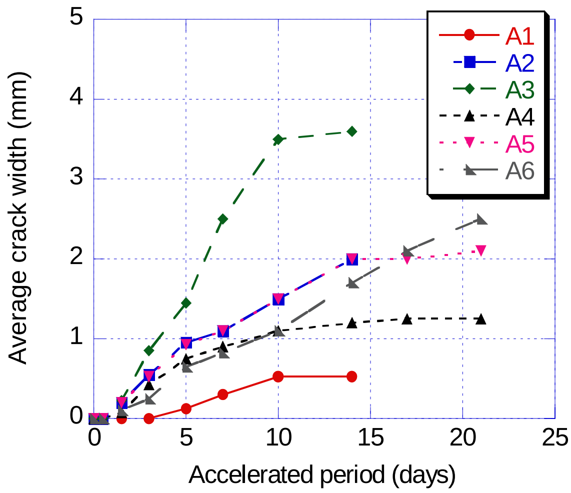


Fig. 7 Average crack width at center section of beams (Series A)

3.2 Relationship between Corrosion Crack and Expansive Pressure due to Corrosion of Sheath and Prestressing Tendon

Figure 8 and 9 show the relationship between average crack width and strains in stirrups for Series S beams. Crack occurred in all specimens with sheath alone (S1 to S4) during the corrosion process. It means that even without prestressing tendon, corrosion of sheath can cause the cracks of test beams. The crack width of the beams and strains developed in stirrups increase with the increase in grouted ratio. Fig. 10 illustrates the mechanism of cracking due to corrosion in the sheath. As the sheath corrodes, the volume of corrosion products rises to 2.5 to 3 times the original sheath volume. This increase in volume generates radial expansive pressure on the surrounding concrete and causes cracking. With more grouting-filling inside the sheath, the expansive pressure becomes larger. In other words, the radial expansive pressure in an insufficiently-grouted beam is lower than that in a fully-grouted beam, because the voids are present in the sheath. Therefore, cracks are observed in a fully-grouted beam earlier than insufficiently grouted beams. This is also the reason why the crack width increases as the grouting level inside the sheath increases.

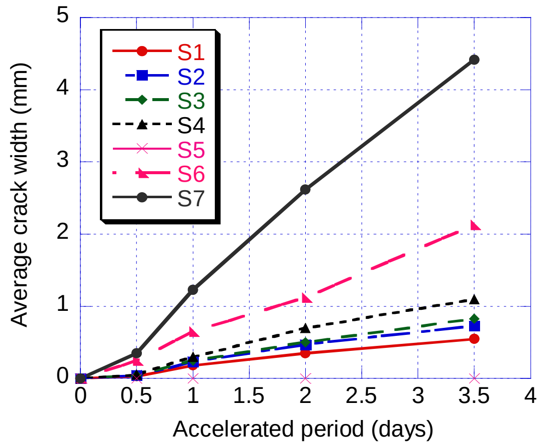


Fig. 8 Relationship between average crack width and accelerated period (Series S)

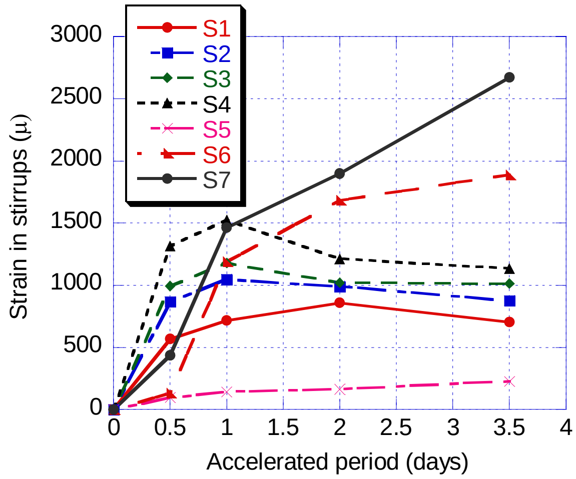


Fig. 9 Relationship between strain in stirrups and accelerated period (Series S)

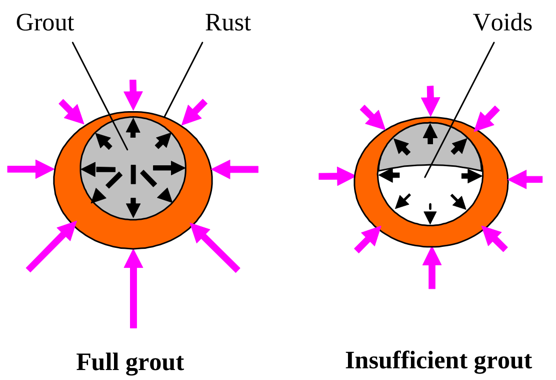


Fig.10 Mechanism of crack due to corrosion

The crack width of the specimen S6 (G66-T) and S7 (G100-T) was almost 2.5 to 3 times larger than that of the specimen S3 (G66-S) and S4 (G100-S). It shows that corrosion of steel tendon has a significant influence on corrosion cracking. The strains developed in stirrups of the beam with tendon was also larger than those of the beam with sheath. After 1 day of accelerated corrosion test, strains of the beams S2, S3, and S4 reduced because corrosion products came out through the cracks in those beams. No corrosion crack occurred in the specimen S5 since the current did not flow well during accelerated corrosion test. Therefore, only a little rust appeared on the surface of the steel tendon and the strains of stirrup in this specimen was very small. It means that expansive pressure due to tendon corrosion in specimen S5 was not sufficient to cause cracking.

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

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

No.	Ultimate failure load (kN)	Weight loss (g)	Weight loss (%)
A0	94.0	0	0
A1	90.2	2	0.3
A2	82.5	5	0.8
A3	72.3	4	0.6
A4	41.2	36	5.5
A5	46.0	33	5.1
A6	47.0	23	3.5

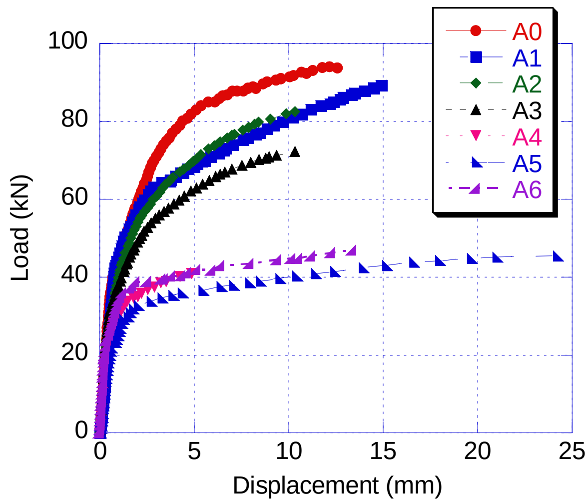


Fig. 11 Load-displacement relationship (Series A)

The results of the loading tests for Series A beams are shown in Table 2, along 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. The control beam, A0, failed at 94 kN. All the other beams of series-A failed at loads lower than that of the control beam. The prestressing tendon in beams with accelerated period of 2 weeks (A1, A2, A3) lost little weight as only a little rust was observed in the prestressing tendons. The steel sheaths in those beams, however, were severely corroded, indicating that the decrease in the load-carrying capacity of the beams with accelerated period of 2 weeks resulted mostly from bond deterioration due to sheath corrosion. The load-carrying capacity reduces with the increase in grouted ratios in the sheath of those beams. The maximum reduction in the load-carrying capacity of the beams with accelerated period of 2 weeks was 23% in the case of beam A3, where the prestressing tendon loses very little weight (0.6 %). This means that corrosion of the sheath causes bond deterioration, resulting in a significant reduction in the load-carrying capacity of the PC beam.

For the beams with accelerated time of 3 weeks, there was severe corrosion and the prestressing tendon almost ruptured at the center part during accelerated corrosion test. The maximum prestressing tendon weight loss was 5.5% for the beam A4. The prestressing tendon weight loss was less in the sufficiently grouted beam than in the insufficiently grouted ones. The load-carrying capacity reduces with the decrease in grouted ratios for the beams with accelerated period of 3 weeks because the prestressing tendon is better protected if grout is filled sufficiently. The main reason caused the reduction in the load-carrying capacity of the beams A4, A5, and A6 is due to corrosion of prestressing tendon. The maximum reduction in the load-carrying capacity was 56% in the case of un-bonded beam A4. This confirms that the corrosion of prestressing tendon has a significant influence on the deterioration of load-carrying capacity of PC beams.

4. CONCLUSIONS

From the results of these experiments, the following conclusions can be drawn:

1. Corrosion-induced cracking tends to occur earlier in fully-grouted beams than in insufficiently-grouted beams. As the grouted ratio in the sheath increases, the corrosion cracks along the sheath propagate earlier during the accelerated corrosion. The width of cracks also increases with the increasing in grouted ratio. As the voids are present in the sheath of an insufficiently-grouted beam, the radial expansive pressure due to corrosion of the sheath becomes lower than that in a fully-grouted beam. Even though the width of cracks become larger in a fully-grouted beam, the prestressing tendon is better protected finally by grouting.
2. Even without prestressing tendon, corrosion of sheath can cause the cracks of PC beams. The width of the corrosion-induced crack and radial pressure due to corrosion of sheath and steel tendon increases with the level of grout in the sheath. Corrosion of steel tendon has a significant influence on corrosion cracking. With the same period of ACTM, the crack width due to corrosion of tendon was 2.5 to 3 times larger than that of corrosion of sheath
3. Corrosion of the sheath deteriorates the bonds with concrete, resulting in a reduced load-carrying capacity of the PC beam. The maximum reduction in load-carrying capacity due to bond deterioration was 23% in the case of fully-grouted beam A3, where the prestressing tendon lost 0.6 % of its weight. For the beams with accelerated time of 2 weeks, due to corrosion of sheath, the load-carrying capacity reduces with the increase in grouted ratios in the sheaths. For beams with accelerated time of 3 weeks, due to corrosion of prestressing tendon, the load-carrying capacity reduces with the decrease in grouted ratios. The maximum reduction in the load-carrying capacity due to corrosion of prestressing tendon was 56%, where the prestressing tendon lost 5.5% of its weight.
4. The experimental methodology presented in this study can be considered to be an effective means to investigate the deterioration of PC beams due to chloride-induced corrosion in a short period.

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