

Deterioration of Prestressed Concrete Beams Due to Combined Effects of Carbonation and Chloride Attack

Rita Irmawaty¹, Daisuke YAMAMOTO², Hidenori HAMADA² and Yasutaka SAGAWA²

¹*Kyushu University, Japan and Hasanuddin University, Indonesia*

²*Kyushu University, Japan*

*West 2 Building, Room 1103, 744 Motooka, Nishi-Ku, Fukuoka, Japan, 819-0395

e-mail: Rita_irmaway@yahoo.co.id, yamamoto@civil.doc.kyushu-u.ac.jp,

h-hamada@doc.kyushu-u.ac.jp and sagawa@doc.kyushu-u.ac.jp

ABSTRACT

Performance of prestressed concrete (PC) beams subjected to both carbonation and chloride ingress has not been clarified well so far. This paper presents the evaluation results and discussion on materials deterioration and corrosion state of prestressing wire/tendons of 35 year's test PC beams. All beams were exposed to the actual marine tidal environments at the Sakata Port more than 20 years, then transferred and stored in a constant temperature over 15 years. The results indicated that all beams showed deterioration on the exterior and the whole surface of beams was carbonated. Even carbonation did not cause corrosion of reinforcement, however, it may have contributed to degradation of cover concrete. In addition, even though tendons were protected by sheath and mortar grouting, however, corrosion area on tendons reached 40%, and prestressing wires corrosion length was 50 to 73%, indicating severe corrosion conditions for PC beams with 30 mm cover depth.

Keywords: corrosion, long-term performance, prestressed concrete

INTRODUCTION

Corrosion of steel reinforcement is one of the important factors affecting long-term durability. Corrosion usually occurs due to either carbonation or chloride attacks, and it has been well researched for both reinforced concrete and prestressed concrete structures for long-term exposure tests. However, performance of prestressed concrete beams subjected to both carbonation and chloride ingress has not been clarified well so far.

In addition, in reinforced concrete and prestressed concrete structures exposed to aggressive environments, cracks play an important role in promoting and accelerating the corrosion process (Lopez-Calvo, 2010 in Mehta). Cracks in concrete can cause the aggressive agents such as chloride ion to come and direct contact with the reinforcing bars in high amounts over a small area, which is the factor in promoting intense pitting corrosion.

In this paper, the long-term performances of prestressed concrete beam with compressive strength target of 50 MPa were evaluated. A series of experimental test was addressed for

materials deterioration and corrosion state of prestressing wire/tendons of 35 year's test PC beams. All beams were exposed to the actual marine tidal environments at the Sakata Port more than 20 years, then transferred and stored in a constant temperature over 15 years. Actually, at 20 years, some beams were already tested, which are reported by Yokota H., et al (1999). The interest was if the environmental condition of specimen was changed to dry from marine wet, then will corrosion stop or continue? In dry condition, carbonation will proceed, so it will be better to know the effectiveness of carbonation after 20 years.

EXPERIMENTAL PROGRAM

Beam Details. A total of 4 prestressed concrete beams were taken out for tests, consisted of two beams of post-tension type (herein after abbreviated as PC-O) and two beams of pre-tension type (PC-R). All beams have the identical cross-section of 150 x 300 mm and length of 2400 mm, but bar arrangements and cover depth are varied according to the type of beam designated. Cover depth is 30 mm for PC-O beams and 35 mm for PC-R beams. Cross-section of the beams is described in Figure 1.

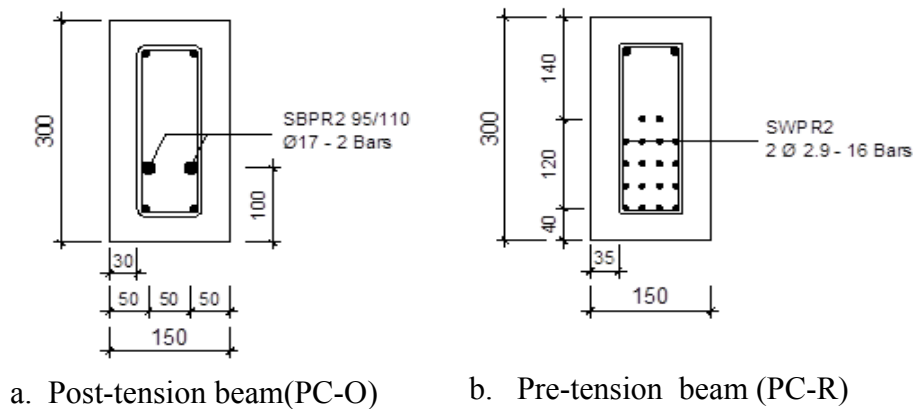


Figure 1. Cross-section of PC beams

The properties of the aggregate are presented in Table 1 and mix proportion of concrete was designed with water/cement ratio (w/c) and sand/total aggregate ratio (s/a) of 40.7% and 37.0%, respectively. High early strength Portland cement is used for making concrete. The composition of material in unit weight (kg/m^3) for water, cement, sand and gravel was 167, 410, 640 and 1175 respectively (Hamada, 1988). The concrete was designed with a slump target of 5 ± 1 cm and air content about $3 \pm 1\%$.

Table 1. Summary of aggregates

Aggregate	Specific Gravity	Fineness Modulus
Fine-river sand	2.55	2.84
Coarse-crushed stone	2.75	6.63

Prestressing tendons were round wires of $2\text{Ø}2.9$ mm in diameter for PC-R beams, and round bars of 17 mm in diameter for PC-O beams. Yield strengths were 1148 and 1795 MPa for the wire and bar respectively. Deformed bars of 10 mm diameter in the PC beams were embedded as stirrups with spacing of 100 mm.

After placing of concrete, the beams were moisture cured for one day and demoulded. Then PC beams were steam cured (maximum temperature 60°C) for about 10 hours, followed by air curing until the start of exposure. Prestress was introduced by the pre-tensioning method for PC-R beam and post-tensioning method for PC-O beam. Effective prestress was about 12.7 to 13.2 MPa for PC-R and 13.7 MPa for PC-O at the bottom fiber of the beam immediately after its introduction. After post tensioning, cement paste was grouted between the bars and the sheath. Also, the ends of each beam were covered with a pad of cement mortar to prevent corrosion of the ends of strands or end anchorages.

Exposure Condition. All beams were exposed to the actual marine environments at the Sakata Port for 20 years, which is located in north-west of Japan (38°56'N, 139°47'E) and faces the Sea of Japan. The beams were placed in the tidal just in front of a caisson-type quay wall two months after placing of concrete, where the beams were subjected to wet and dry conditions alternately due to tidal action (Yokota, 1999).

The beams can be categorized into two conditions in term of pre-cracking, i.e. 'A' and 'B'. Condition A refers to pre-cracked, for which beams were pre-cracked by bending moment until 65% of the ultimate bending moment. After cracking, the bending moment was released, and no continuous load was applied during exposure. Condition B refers to no pre-cracks. Summary of the beam specimens were presented in Table 2.

Table 2. Summary of PC beam specimens

Type	Cover Depth (mm)	Cracking and Loading Condition	Effective Prestress (MPa)
PC-O-1	30	B	13.7
PC-O-2		B	
PC-R-1	35	B	12.7 - 13.2
PC-R-2		A	

After 20 years of exposure, the beams were transferred to the laboratory and stored at a constant temperature over 15 years as shown in Photo 1. Then beams were taken out for laboratory tests. All tests were conducted in conformity with JIS, JSCE and ASTM.



Photo 1. PC beam specimen

Test Item and Method. First, the surfaces of beams were cleaned, and the presence of rust stain, air bubble, chips and cracks were observed. Then specimens were investigated for steel bar corrosion by using half-cell potential and anodic polarization curve by contact method. The half-cell potential was measured at an interval of 200 mm at four strands with various cover depth, stirrups and steel bar. Whereas polarization curve were measured at three points (20 cm from both ends and in the center of specimen) on the same bars. The measurement was conducted with silver/silver chloride electrode after 1 hour pre-wetting.

To obtain the mechanical properties of the specimens, ultrasonic pulse velocity (UPV) was conducted by the direct method with an interval of 200 mm and path length of 150 mm. Several cores of 50 mm in diameter were taken from each beam for compressive strength, carbonation depth, porosity and chloride content measurements. Finally, ratio of portion surface area that was corroded corresponding to all surface area of steel bar was measured.

DEGRADATION OF CONCRETE

Appearance of Beams. Figure 2 shows the cracking traces of beams. These figures show the side surfaces of the respective beams just after cleaned by steel brush. Uncovered aggregate were mostly found on the bottom side of beams due to seawater splashing, while rust stains commonly found at the ends of beams and in the vicinity of the cracks.

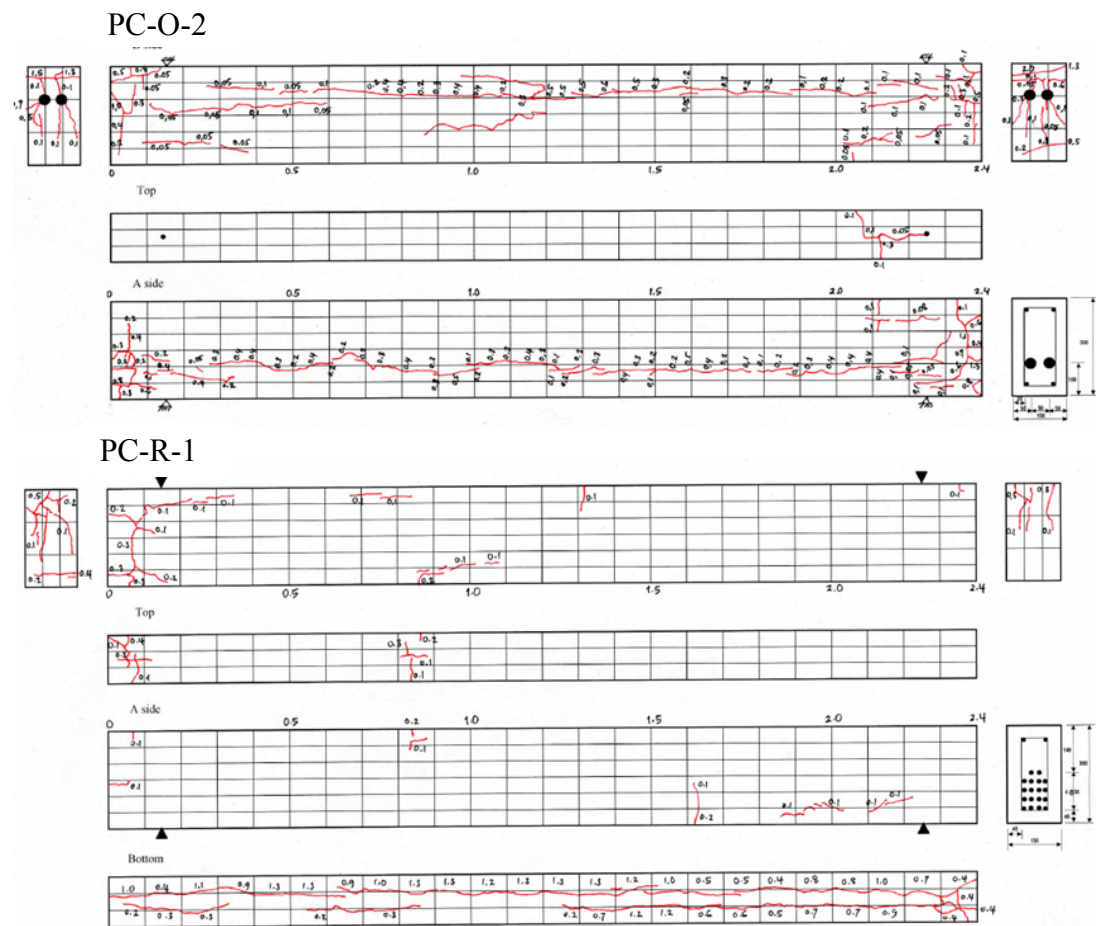


Figure 2. Appearance of beams over 35 years of exposure

After exposed up to 35 years, all beam surfaces appeared rough surfaces, chips on the edges and a few spalling especially in PC-O beams. At the scale area, the maximum cracks width is about 1.5 mm for PC-O and 1.3 mm for PC-R. Air bubbles of 1-13 mm in diameter also appeared in each beam.

Deterioration of concrete is clearly observed from all PC beams, particularly the end parts damaged severely, and PC-O beams indicate extensive damage visually compared to PC-R beams. The result of the appearance at 20-year test, shows the maximum crack width was 0.2 mm and cracks concentrated in the ends of the beam. It seems that there was a large degradation over a period of 15 years in PC-O beams.

Mechanical Properties. The compressive strength and elastic modulus of concrete in 35-year test of PC beams is presented in Figure 3. Compressive strength values vary in a wide range from 42.10 to 77.03 MPa, with a coefficient of variation is 4.9. The mean value of strength is 67.8 MPa and 45.24 MPa for PC-O and PC-R, respectively. Modulus data was taken during the compression test, and their values vary from 21.6 to 30.9 GPa, with an average value of 29.1 GPa and 24.6 GPa for PC-O and PC-R, respectively. The elastic modulus losses up to 10% compared to the 20-years' data. On the other hand, the variation data for pulse velocity is low, which shall be equal to 4.30 and 4.13 km/s for PC-O and PC-R respectively, indicating good condition. The variation of the data is expected due to different shape and size of specimen test, that is in this 35 years test, small cores taken from beam were used, however, in 20 years test, Ø150 x 300 mm cylindrical specimens were used.

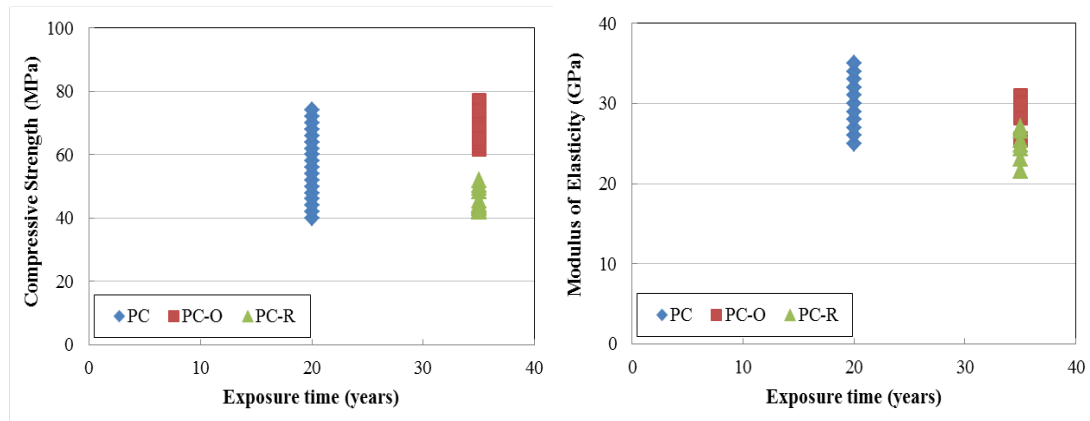


Figure 3. Compressive strength and elastic modulus

Porosity and Chloride Content. Total pore volume and pore size distributions of the mortar matrix collected at 10-20 mm depth of the specimens are shown in Figure 4. Pore size distribution in the capillary pore range exhibited the same trend for all specimens. From the view point of total pore volume, PC-R beam shows that total pore volume is similar between 20 and 35-year test, while pore volume of PC-O beams rose up 18% during 15 years. It indicates that deterioration on the exterior is in progress and may cause permanent damage to the surface of the beam.

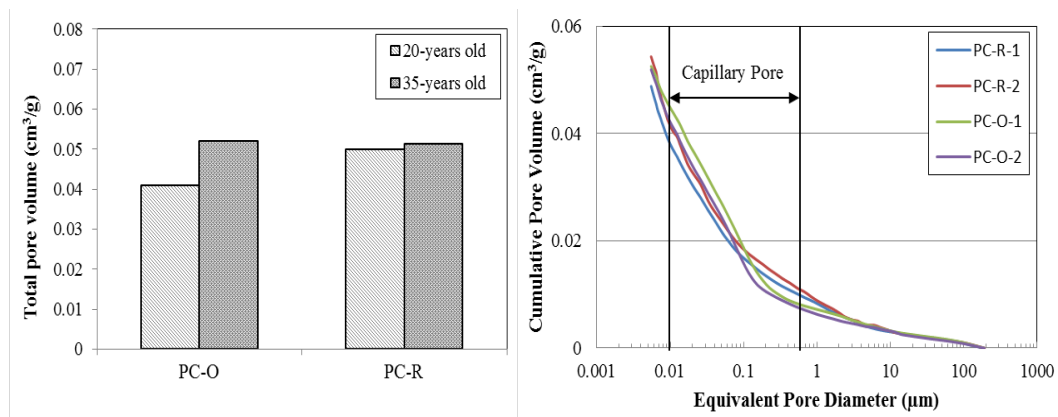


Figure 4. Total pore volume and pore size distribution

Profile of chloride ion ingress into concrete for each beam was obtained from 35-year test of PC beams is shown in Figure 5. Total chloride content on the surface of concrete is lower than a certain depth from surface. It indicates that most of the chloride ions migrated and concentrated near the steel bar surface. Comparing chloride profiles of PC-O and PC-R, it is seen that the total chloride content in the surface of PC-O beams is lower than PC-R beams. Conversely, at a depth of 2.5 cm from the surface, the chloride content of PC-O beams is higher than PC-R beams. This is considered due to an increase in total pore volume, which makes chloride ions easier to migrate and reach the steel surface, thus lead to the onset of corrosion.

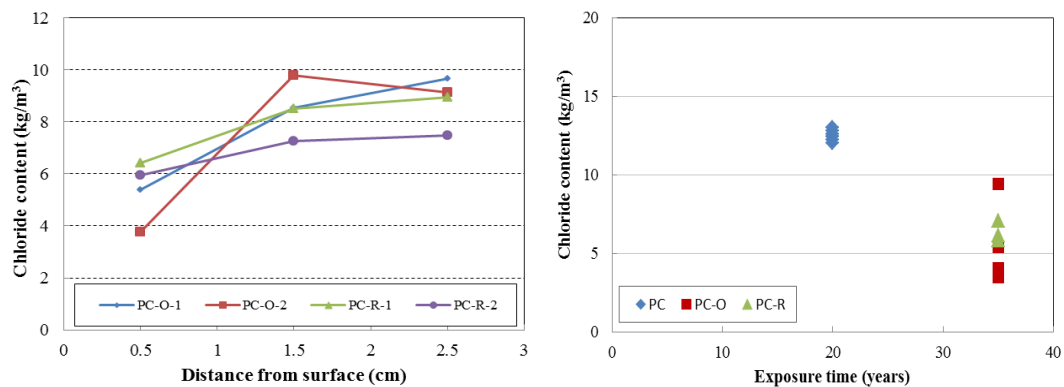


Figure 5. Chloride ion profile

From 20 and 35 years' test results, chloride content in concrete of 35 years is smaller than that of 20 years. This is probably due to the effects of the size and shape of specimens. For 20 years test, $\text{Ø}150 \times 300$ mm cylinder specimens were used, however, in this 35 years test, small core of $\text{Ø}50 \times 100$ mm taken from beam were used, that is, the chloride content of cylinder specimens is much higher than beam specimens.

A core sample was taken near the surface of the corroded reinforcement, and then chloride content was measured. The results were about 16.37 kg/m^3 at a depth of 2.5 cm. This value is very large compared to 1.2 kg/m^3 chloride content, which are considered in the concrete for corrosion initiation. Since chloride content of around 2.0 to 4.0 kg/m^3 could be assumed

as chloride threshold value for initiation of steel corrosion, it indicates that corrosion probably initiated at least 20 years-old.

Carbonation Depth. The application of phenolphthalein to the core sample of PC beams reveals that the whole surface of the beams was carbonated. The rate of carbonation was up to 0.845 mm/ $\sqrt{\text{year}}$ for PC-O beams and 0.507 mm/ $\sqrt{\text{year}}$ for PC-R beams. The large carbonation rate in PC-O beams seems to be affected by an increasing in total pore volume, so that CO_2 in the atmosphere diffuses easily into the pore system of concrete and react with calcium hydroxide ($\text{Ca}(\text{OH})_2$) in the presence of moisture to form calcium carbonate (CaCO_3). Actually, the process of carbonation is slow in good quality concrete with water/cement ratio of 40.7%, which is 0.55 mm based on JSCE formula. This indicates that the presence of chloride ion in the concrete accelerated the carbonation process.

CORROSION MONITORING AND CORROSION AREA

Natural Electrode Potential Test and Corrosion State of Steels. The results of half-cell potential measurements in PC-R beams are presented in Figure 6, which is grouped according to ASTM C876-91 (1999). The measurement was conducted with silver/silver chloride electrode after 1 hour of pre-wetting. Then measured value was converted to the potential of the copper/copper sulphate electrode (CSE) at 25°C. In fact, depth of carbonation is very thin (only 3 mm) compared to 35 mm cover depth, thus, it can be assumed that carbonation of the concrete did not cause corrosion of the reinforcement, however, it may have contributed to degradation of the cover concrete.

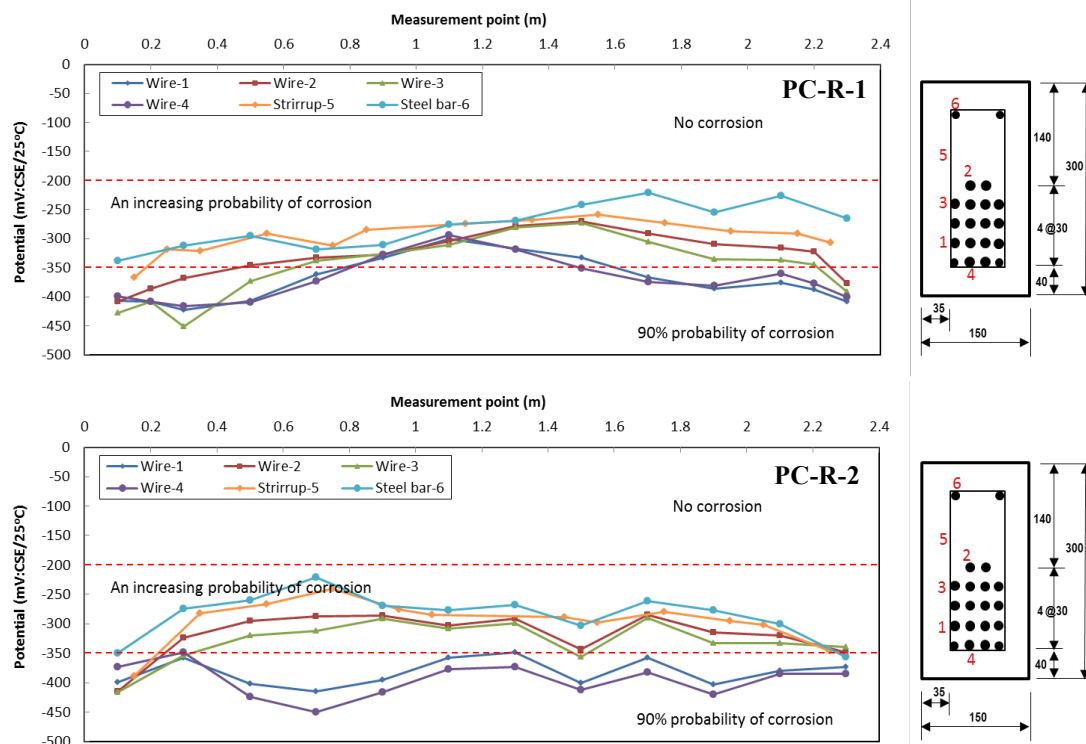


Figure 6. Half-cell potential: PC-R-1 (no-cracked), PC-R-2 (pre-cracked)

Figure 6 shows the potentials of reinforcement, both prestressing wires and steel bars. It can be seen that the potential of the wire-1 and wire-4 in both beams dropped to a value less than

-350 mV vs CSE, thereby indicating breakdown of the passive layer. In PC-R-2 beam, as expected, value of the potential of wire-1 and wire-4 became more negative than PC-R-1 beam due to pre-cracking before exposure test.

In any case, researchers agree that over a long design life (100 year design life) the presence of cracks only accelerates the initiation of corrosion (Robert, 2011 in Ahern, 2005). In the case of PC-R-2 beam which is pre-cracked before exposure test, measurement of total chloride content was the lowest compared to the other beams as shown in Figure 5, however, it presented a higher risk of corrosion. It seems that pre-cracking has accelerated the initiation of corrosion.

In addition, the ends of wire-2 and wire-3 have corroded due to no concrete cover, while the other side of strands indicated an increasing probability of corrosion with potential value from -200 to -350 mV. In the stirrups and steel bars, the potential value identified less negative than all the strands were measured. This is caused by the position of measurements on the upper side stirrup which most of them have not yet corroded.

The corrosion rate measured using polarization resistant represent the rate at the time of the test. The corrosion rate at a particular point in a specimen will depend on several factors, such as temperature, concrete resistivity and oxygen availability. Then corrosion rate is expressed as the corrosion current density, i_{corr} , is inversely related to the polarization resistance. Interpreting of corrosion rate measurements is described in Figure 7 based on the finding of Andrade, 1996. From this figure, it can be concluded that most of the prestressing wires and reinforcements are getting rusty with different levels of corrosion risk.

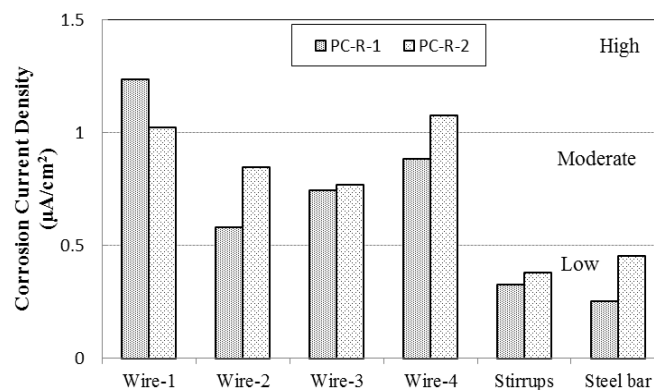


Figure 7. Interpretation of corrosion risk

Polarization Curve. PC beams which were located in the tidal marine environments are a critical condition for corrosion initiation, where wetting and drying cycle favor the presence of both oxygen and chlorides. Polarization curve measurement was conducted on PC-R beams at 3 point and typical result is presented in Figure 8. This figure shows, all the reading were appropriated for extensive corrosion and they are categorized as Grade-1, except stirrups and steel bars in PC-R-2 as Grade-2. Most of the strands and stirrups had an i_{corr} value higher than $10\mu\text{A}/\text{cm}^2$ indicating that active corrosion is taking place. Only a few steel bars had an i_{corr} value less than $10\mu\text{A}/\text{cm}^2$, denoting that moderate corrosion was occurring. Corrosion initiation was accelerated by high oxygen availability. Increasing in the rate of corrosion likely occurred over the past 15 years, when beams were stored at constant

temperatures, where the presence of both chloride ions in the pores of concrete and oxygen supply was more than enough, and an ideal condition for corrosion process.

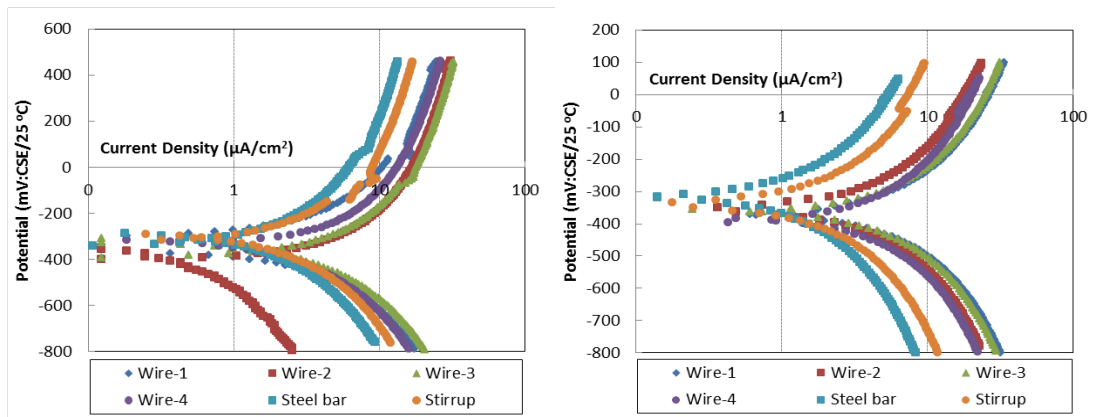


Figure 8. Anodic-cathodic polarization curve; PC-R-1 (left), PC-R-2 (right)

Corrosion State of Pre-stressed Tendon/wire and Steel Bars. Photo 2 and 3 show corrosion state of longitudinal bars, stirrups, tendons/prestressing wire and anchorages. Most of the longitudinal bars on the tensile zone of beam suffered severe corrosion, instead, steel bars in the compressive zone show the better condition. The same pattern was also shown by stirrups, the bottom side mostly suffered quite severe corrosion while the top side remains in good condition.



Photo 2. The state of reinforced bars of PC-O beam

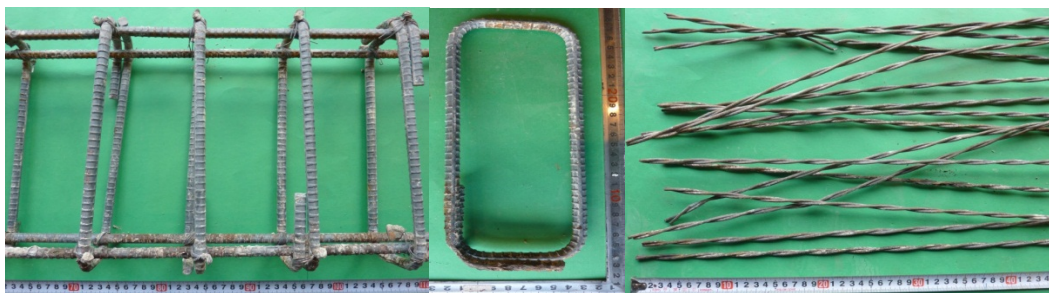


Photo 3. The state of reinforced bars of PC-R beam

The measurement of corrosion area was conducted on tendon, while for prestressing wire, length of wire corrosion was measured. Even though tendons were protected by sheath and

grouting mortar, however, corrosion area on tendon were large enough, i.e. 19.70% and 40.56% for PC-O-1 and PC-O-2 beams, respectively. This results show severe corrosion conditions for 35 years-test of posttension beams with 30 mm cover thickness. The same trend was also found in pretension beams, where the length of wire corrosion was 51.07% and 73.51% for PC-R-1 and PC-R-2, respectively. This value indicates that pre-cracked in PC-R-2 has accelerated the corrosion of reinforcing bars.

CONCLUSION

Based on the evaluations, the following conclusions are drawn:

1. The large degradation appeared on the PC-O beams visually, with a maximum crack width of 1.5 mm, horizontal cracks along the side of beam parallel to the tendon and in the anchorage area, also spalling on the side surfaces of beams which showed that deterioration on the exterior is in progress.
2. In view point of mechanical properties, test data of PC-R beams showed a sharp decrease in the compressive strength and modulus of elasticity. This is expected due to different shape and size of specimen test, in this 35 years test, small cores from beam were used, however, in 20 years test, $\text{Ø}150 \times 300$ mm cylindrical specimens were used.
3. The increase in total pore volume in the PC-O beams, caused chloride ions migrated easier and concentrated near the steel bar surface, and then reacted with the ferrous and hydroxyl ions to form various corrosion products.
4. The application of phenolphthalein to the core sample of PC beams reveals that the whole surface of the beams was carbonated, and the rate of carbonation is up to 0.845 mm/ $\sqrt{\text{year}}$ for PC-O beams and 0.507 mm/ $\sqrt{\text{year}}$ for PC-R beams.
5. The combination of chloride attack and carbonation, increased corrosion area of tendon in PC-O beams and most of the strands in PC-R beams, while pre-cracking accelerated the corrosion process of embedded reinforcements.

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