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CORROSION BEHAVIOUR OF PRESTRESSING WIRES EMBEDDED IN OPC AND PPC CONCRETES

J.RAMA RAVI

M.E. Structural Engineering Student, CMS College of Engineering, Namakkal.

ABSTRACT:
Corrosion of steel embedded in reinforced concrete and prestressed concrete structures are a global problem. In general, corrosion in reinforced concrete structures shows some symptoms of failure before any catastrophic failure. But, in prestressed concrete structures, sudden catastrophic failure occurs without any symptoms of failure. This could be due to the conjoint action of stress and corrosion on prestressing wires embedded in concrete. It can be seen from the literature that very little data is available on corrosion of prestressing wires embedded in prestressed concrete structures. In the present study, an attempt has been made to generate data on corrosion of prestressing wires embedded in concrete. Pre-tensioned concrete beams have been cast with several 7 mm prestressing wires. The corrosion behavior of prestressing wire has been studied in two different concretes viz. OPC and PPC. Before initiating corrosion measurements, the corresponding pre-tensioned beams have been periodically subjected to 3% Sodium Chloride solution or distilled water in order to create accelerated corrosion by way of alternate wetting and drying condition. Corrosion behavior of embedded prestressing wires has been monitored by

1.1 INTRODUCTION

According to the ASTM terminology (G 15) corrosion is defined as "the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties." As per the IRC recommendations, the service life of reinforced concrete structures is about 60 years. Unfortunately, the structures show signs of deterioration such as spalling of cover concrete and cracking, before the stipulated service life due to various factors like climatic conditions, aggressive environments, etc., which lead to corrosion of the reinforcement bar. However, in prestressed concrete structures, sudden catastrophic failure occurs without any such symptoms of failure. This could be due to the conjoint action of stress and corrosion on prestressing wires embedded in concrete.

Corrosion of prestressing steel is a widespread concern. Because the cross-section of each prestressing wire or strand is small and the steel is already under significant stress, a much smaller cross-section loss from strand or wire (compared to reinforcing bar) will cause the strand to deboned from the concrete and eventually break. In addition, it may corrode without producing outward evidence such as rust staining, cracking or spalling because the tensile stresses that the small cross-section of steel generates in the cover concrete are small. Consequently, the strand or wire may debond or break without warning. If it breaks, it may burst from the concrete where the cover concrete cannot withstand the prestressing forces released by the failure. Once one wire (or strand) breaks, its load is redistributed to others that may

not have the residual capacity to sustain the extra load, so the risk to the element increases very quickly. Management of reinforcement corrosion is usually based on a need to maintain the appearance of the structure, prevent damage or injury caused by spalling concrete, or delay the rate of corrosion

1.2 OBJECTIVE

- The main objective of this work is to study the corrosion behaviour of prestressing wires embedded in OPC and PPC concretes subjected to marine environment and normal environment.
- In addition, Potential time measurement and Cable resistance measurement were carried out on prestressed concrete beams in OPC and PPC

2 MATERIALS

2.1 CEMENT

Cements used for RCC, PSC test specimens and cement extracts for solution study were Ordinary Portland Cement (OPC) and Portland Pozzolana Cement (PPC)-53 grades conforming to IS 12269: 1987

2.2 FINE AGGREGATE

Clean and dry river sand available locally will be used. Sand passing through IS 4.75mm sieve will be used for casting all the specimens Natural fine aggregate conforming to zone III was used as fine aggregate for casting RCC and PSC test specimens..

2.2.1 COURSE AGGREGATE

Natural blue metal obtained from local quarries was used as coarse aggregate for casting RCC and PSC test specimens. The maximum size of coarse aggregate used was 20 mm. Two fractions of coarse aggregate were used for casting viz.,
Fraction-I:
10 to 20 mm - 60 %
Fraction-II:
< 10 mm – 40 %

2.3 WATER

Distilled water was used for casting and curing of the RCC and PSC test specimens. Double distilled water was used for the preparation of cement extract.

2.4 Prestressing Steel Wires

7 mm diameter prestressing steel wires with tensile strength of 1470 N/mm2 conforming to IS 875 (Part-I): 1960. The prestressing wires at top and bottom were prestressed to 30 % and 65 % of its inherent tensile strength.

2.5 CHEMICALS USED FOR EXPERIMENTAL INVESTIGATION

Chemicals used for experimental investigations in the present study on corrosion behavior of PS wires are discussed here.

2.5.1 Sodium Chloride

Sodium Chloride (NaCl) varying from 0 to 3% was used in the various performance investigation studies of PS wires.

2.5.2 Sodium Hydroxide

Sodium Hydroxide (NaOH) solution of 0.04 N was used in this study.

2.5.3 Cement Extract

Cement extracts (CE) prepared with Ordinary Portland Cement and Portland Pozzolano Cement of 53 grades with water cement ratio of 2: 1 was used for electrochemical studies. These extracts acted as the control medium for various experiments.

Table 2.1 Inherent Chloride content in OPC and PPC cement extracts

S.No.	Type of cement extract	Chloride content (ppm)
1.	Ordinary Portland cement (OPC)	160
2.	Portland pozzolano cement (PPC)	180

2.5.4 Potassium Chromate

Potassium Chromate (K2CrO4) was used as an indicator in the chloride estimation test.

2.5.5 Silver Nitrate

Silver Nitrate (AgNO3) of 0.1 N was used as burette solution in the chloride estimation test.

2.5.6 Concrete mix ratio

The concrete mix proportion was designed as per IS: 10262-2009 for M40 mix
And it was found out to be 1: 1.72: 3.20 with a w/c ratio of 0.49.

3. EXPERIMENTAL PROCEDURES

3.1 COMPRESSIVE STRENGTH TEST

Before commencement of casting of PSC specimens for various studies, plain concrete cubes have been cast as per the designed mix in order to find out the cube compressive strength. the PSC cube specimens were taken out from water and tested for the compressive strength using AIMIL Compressive testing machine. The maximum load for each specimen was noticed and the characteristic compressive strength was calculated from this load. This compressive strength has been found out for two curing periods viz., 7 and 28 days.

3.2 TIME TO CRACKING STUDY

Cylindrical concrete specimens of size 6 x 10 cm with design strength of M40 were cast for this study. After curing period was over, the respective PSC specimens were subjected to Time to cracking study. During testing, the respective PSC specimens were kept in the cylindrical container. A perforated stainless steel plate in cylindrical shape was kept around the test specimen. Then 3% NaCl Solution was filled up to the top surface of the test specimen. This setup is connected to a power supply unit through wires.

3.3 POTENTIAL TIME STUDIES

The probability of PS wire to corrode is assessed by measuring the open circuit potential (OCP) of embedded PS wire with respect to a standard reference electrode. OCP being a thermodynamic quantity, as such, will not indicate the extent and rate of corrosion. A digital voltmeter is used to measure the OCP. Saturated Calomel Electrode (SCE) is used as reference electrode. After the curing period was over, the initial open circuit potential measurements were made on the PS concrete beams made with PPC and OPC for M40 concrete, just before subjecting the PS beams to alternate wetting and drying of either 3% NaCl or distilled water conditions.

3.4 CABLE RESISTANCE MEASUREMENT

Corrosion condition of PS cable can be assessed by making direct electrical resistance measurement. This technique which is used to measure the resistance of prestressing wires is known as four probe technique. As soon as the curing period of PS beams has been completed, they were taken out from the curing tank and allowed to dry. Later, electrical connections were taken from each PS wire ends by soldering. Each PS wire will have one current terminal and one voltage terminal. Hence, totally two terminal points were taken from each wire ends. Similarly, electrical connections were taken at the other end of the prestressing wire. Later, all the soldered portions were completely protected using a chemical compound.

3.5 CARBONATION STUDY

In order to determine the depth of carbonation of the PS beams, carbonation test was carried out on PS concrete beams exposed to distilled water and 3 % NaCl conditions.30 mm diameter and 50 mm deep core samples have been taken on the respective PS beams using concrete core drilling machine

4 SOLUTION STUDIES

4.1 Preparation of Cement Extract

Cement extract has been prepared with both OPC and PPC cements for electrochemical studies. At first, 100 grams of OPC/PPC was accurately measured using a digital balance and it was transferred to a 500 ml conical flask. Then 200 ml of distilled water (1:2) is added to the respective cement and thoroughly mixed. Then 16 conical flasks containing cement and water mixture are rigidly fixed in the spring mounted clamps of the electronic shaker. The shaker is run for one hour. Then the cement water mixture is filtered through No.1 Watt man filter paper. This filtered solution is known as cement extract (CE). This will act as control (without addition of chloride) for various experiments.

PH of the above prepared cement extract was measured using digital pH meter. Initially pH meter was calibrated for at least three times using standard buffer solution (pH = 9.0) to obtain the accurate result. pH electrode was immersed in a beaker containing sample. Values were directly shown by the digital pH meter. For more accuracy, above steps were repeated for at least three times per sample and average value was taken.

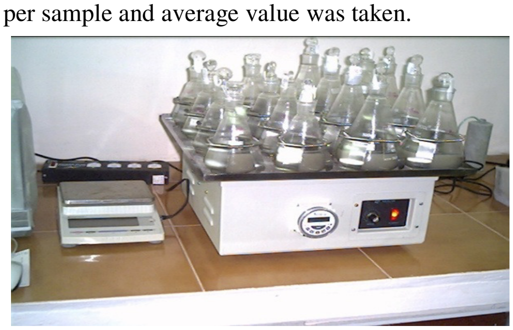


Fig 4.2 Preparation of cement extracts

4.2 Addition of Chloride

The cement extract for OPC/PPC is prepared as per the above procedure. Required amount of chloride will be added to the above extract in the form of NaCl to simulate the chloride environment. The amount of chloride in percentage used in various evaluation tests is given below.

Table 4.1 Amount of chloride used in various evaluation tests

S.No.	Technique	Amount of chloride (ppm)
1.	Anodic Polarization	0 to 400
2.	Potential Time Behaviour	10000
3.	Linear Polarization Resistance	1000
4.	Tafel Technique	1000

4.3.2 ELECTROCHEMICAL STUDIES IN CEMENT EXTRACT

4.3.1 ANODIC POLARIZATION

In order to study the tolerable limit for chloride of prestressing steel wire in PPC/OPC extract with and without chloride, an accelerated electrochemical technique known as Anodic Polarization technique has been carried out. Differing amounts of chloride varying from 0 to 400 ppm of chloride in the form of NaCl is added to the cement extract. Prestressing steel wire of size 7 mm diameter and 80 mm length is used as working electrode. In this 80 mm length of PS wire, 0.2827 cm2 area is exposed to the respective medium. The remaining portion of the PS wire is carefully masked with 1 mm thick Teflon tape. Initially, the open- circuit potential of PS wire is measured against Saturated Calomel Electrode (SCE). Then it is anodically polarized by applying a current of 290 µA/cm2 through a platinum foil auxilary electrode. The variation in potential with time is measured every 30 seconds with a digital voltmeter. The total duration of the test is 5 minutes. This experiment is carried out for two medium viz., CE and CE+Cl of the respective cement. Table 5.3 indicate the data on anodic polarization test carried out for the PS wires exposed in PPC and OPC extract respectively.

4.3.2 POTENTIAL TIME STUDIES

To study the potential time behaviour of PS wire in the cement extract made up of OPC/PPC with and without chloride as per ASTM C 876-2010. The corrosion behaviour of PS wires exposed in respective cement extract (with and without chloride) is studied using open-circuit potential measurement with respect to a Standard Calomel Electrode (SCE). A digital voltmeter with an accuracy of ± 10 mV was employed for this study.

4.3.3 LINEAR POLARIZATION TECHNIQUE

To study the corrosion behaviour of PS wires in the cement extracts made up of OPC and PPC (with and without chloride) using Linear Polarization Technique.

The corrosion behaviour of PS wires exposed in respective cement extracts has been studied by Linear Polarization Technique. The corrosion behaviour was determined by Polarization studies using conventional three electrode system. For this study, the working, reference and counter electrodes are same as the reference and the counter electrodes used as anodic polarization studies. This test was carried out using an electro-chemical measurement unit.

The PS wire was immersed in the respective cement extract and the Open circuit potential; (OCP) was measured initially. In this method, the potential current behaviour was studied in the potential region of ±20 V at the vicinity of OCP. Later the polarization resistance (RP) was predicted from the slope of the polarization curve. The linear polarization data collected on PS wires exposed in OPC/PPC cement extracts are given in Table 5.4 respectively.

4.3.4 TAFEL TECHNIQUE

The corrosion behaviour of PS wires exposed in OPC/PPC cement extracts has been evaluated by TAFEL technique. The conventional three electrode system has been adopted in this method. Using an electro-chemical measuring unit this experiment was conducted.

5. RESULTS AND DISCUSSIONS

5.1 COMPRESSIVE STRENGTH TEST

The compressive strengths for OPC and PPC concretes cured for 7 and 28 days are presented in Table 5.1. It can be seen from the table that OPC exhibits higher strength than PPC at the end of 7 day curing. More or less equal value of around 44 N/mm2 compressive strength was obtained at the end of 28 days of curing for both the cements.

Table 5.1 Compressive strength of OPC and PPC concretes

S.No.	Age of specimens	OPC	PPC
1.	7 days compressive strength (N/mm2)	35.67	28.36
2.	28 days compressive strength(N/mm2)	45.33	43.85

5.2 TIME TO CRACKING STUDY

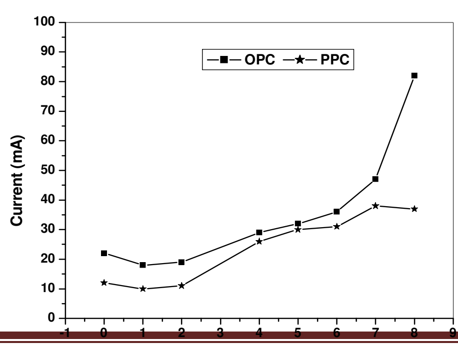


Fig.5.1 Current measured during time to cracking study

The results for this test are graphically represented in Fig.5.1. It can be seen that the PS wire embedded in OPC concrete shows higher current than the PS wire embedded in PPC concrete. At the end of the experiment, more than two times the initial current value was found in the PS wire embedded in OPC concrete.

5.2.1 Top Left in salt water

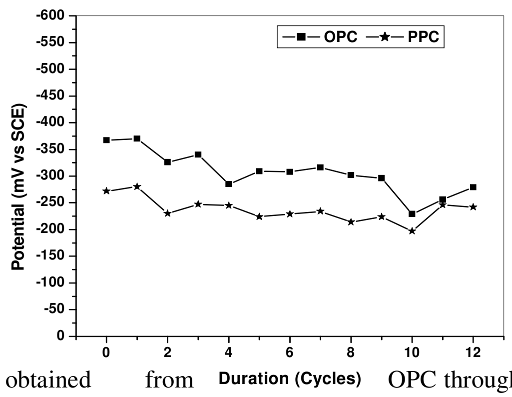


Fig.5.2 s

obtained from OPC throughout the test period.

5.2.2 Top right in salt water

Fig.5.3 shows the potential variation of PS wire embedded in OPC and PPC concrete exposed to salt water condition at top right portion. It can be seen from the figure that the potential of PS wire varies from -264 to -374 mV through the test period of 12 cycles in OPC concrete. Whereas, the potential in PPC concrete varies between -199 to -286 mV. Here again, all the potential values of PPC concretes are lower than that of OPC concretes.

5.3 CABLE RESISTANCE MEASUREMENT

5.3.1 Top left in salt water

Fig.5.10 shows the cable resistance data obtained on PS wire embedded in OPC and PPC concretes exposed to salt water condition located at top left portion. Irrespective of the cement type, the resistance values vary between 8.5 to 8.7 mΩ throughout the test period. Under this condition, both the concretes behave in similar fashion.

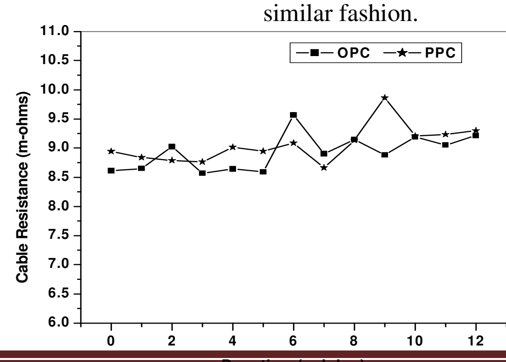


Fig.5.3 Cable resistance of PS wires located at TL

5.3.2 Top right in salt water

Fig.5.4 shows the cable resistance data obtained on PS wire embedded in OPC and PPC concretes exposed to salt water condition located at top right portion. Here again, the PS wire embedded in OPC and PPC concretes behave in similar manner. The variation between OPC and PPC concrete is not appreciable.

Initially, the cable resistance values of the PS wires embedded in OPC concrete is higher than that of the resistance values of the PS wires embedded in PPC concrete during the first three cycles. During the next four cycles, there is not much variation in resistance value for both the concretes.

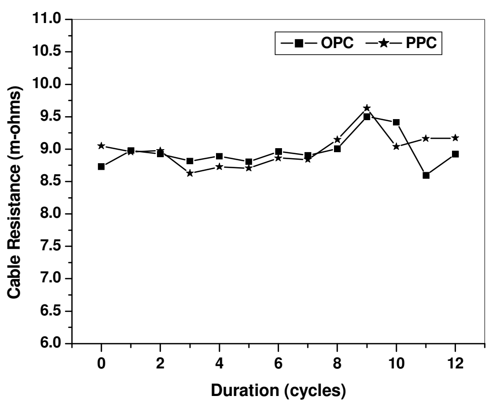
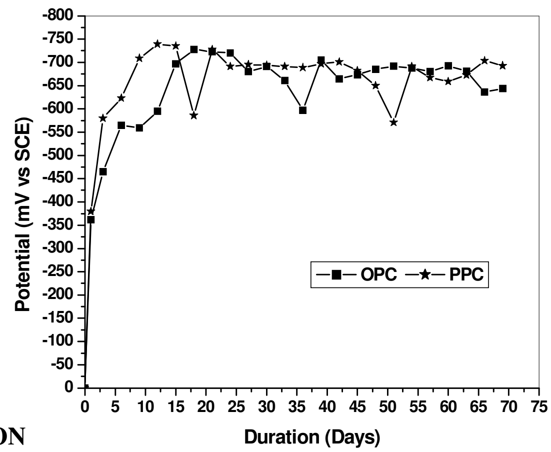


Fig.5.4 Cable resistance of PS wires located at TR in SW

5.4 CARBONATION STUDY

Figs.5.18 and 5.19 show the carbonated core samples taken from OPC and PPC concretes subjected to 3% NaCl exposure condition respectively. Figs.5.20 and 5.21 show the carbonated core samples taken from OPC and PPC concretes subjected to distilled water condition respectively. From the figures, it can be seen that irrespective of the type of cement and type of exposure, carbonation occurred only on the top surface. There was no penetration of carbonation on the depth of core samples which was confirmed by the appearance of pink color when sprayed with phenolphthalein indicator.

Fig.5.5 OPC core samples subjected to 3 % NaCl



5.3 SOLUTION STUDIES

5.3.1 ANODIC POLARIZATION

The anodic polarization behavior of PS wire immersed in OPC and PPC cement extracts (with and without chloride) is shown in Table5.3. It can be seen from the table that the PS wire embedded in OPC extracts (with and without chloride conditions) show steady state potential throughout the test period. In PPC extract with chloride condition also similar behaviour can be observed. From that, it can be concluded that under these environments, PPC wire is quite safe. As a contrary, the PS wires in PPC cement extract exhibit few rust product on the surface

Table 5.1 Anodic polarization behavior of OPC and PPC extracts with and without chloride

S. No.	Medium	OCP (mV)	Voltage at 5 seconds (mV)	Voltage at the end of experiment (300 seconds) (mV)
1.	PS wire in OCE alone	-326	-556	-710
2.	PS wire in PCE alone	-324	-418	-186
3.	PS wire in OCE + 1000 ppm Cl	-349	-347	-323
4.	PS wire in PCE + 1000 ppm Cl	-192	-73	-165

5.5 POTENTIAL TIME STUDIES

5.5.1 Cement extract without chloride

The variation of potential of PS wires immersed in CE (without chloride) made with OPC and PPC cements is shown in Fig.5.22. It can be seen from the figure that the potential values of PS wire fluctuates with time in PPC extract. However, majority of the potential values in OPC extract was lesser than the values obtained in PPC extract. It can be clearly seen from the figure that the potential value corresponding to the PS wires embedded in PPC extract dips to a much lower value than the potential values measured in the PS wires embedded in OPC extract. Similar trend can be observed in OPC extract during the thirty sixth day. After forty six days of immersion of the PS wires in the extracts, the measured potential values of the PS wires embedded in OPC extract is slightly higher than that of PPC extract.

5.5.2 Cement extract with 1% chloride

Fig.5.23 shows the variation of potential of PS wires immersed in OPC and PPC extracts with 1 % chloride. Under this condition, the behavior of PS wires immersed in OPC extract was reversed when compared to CE alone. Here, the potential of PS wires in PPC extract was almost in steady state condition. Whereas the potential of PS wires embedded in OPC extract fluctuated with time. Even though there is a wide variation between OPC and PPC during earlier stages, the measured potential was almost very close in both the extracts after 60 days of exposure.

CONCLUSION

8.1 GENERAL

From the results of the experimental investigations carried out in this study, the following conclusions can be drawn.

8.2 CONCLUSION

Based on the experiment the following conclusion is drawn within the limitation of test results.

- The compressive strength test results show that the concrete made with OPC exhibits higher 7 day and 28 day strength than the concrete made with PPC
- In the time to cracking study, the cylindrical RCC specimens made with OPC concrete exhibited symptoms of cracks as well as cracks on the external surface much before the PPC specimens. The delayed effect of cracking in the PPC specimens could be due to the presence of pozzolanic material.
- The carbonation study revealed that there was no penetration of carbonation on the depth of core samples. The samples clearly showed that carbonation had occurred only on the top surface.
- Potential time studies carried out on the PS beams reveals that the potential of the PS wires embedded in PS beams made with OPC concrete located at bottom subjected to marine exposure condition was the highest of all conditions. Higher potential values suggest that the pertaining PS wires are susceptible to higher proabability of corrosion than the other counterparts. This may be due to the absence of pozzolanic material and severe environmental exposure condition.
- The variation of cable resistance data is not appreciable in different locations such as top left and right portions exposed to salt water condition and top left portion subjected to distilled water condition embedded in OPC and PPC concretes. For the other locations, the cable resistance of the PS wires pertaining to PPC concrete is slightly higher than that of OPC.
- The potential time study carried out in simulated environment also shows that the PPC extracts with and without chloride exhibit lower potential values than the OPC extracts. This clearly shows that the probability of corrosion is higher in OPC extracts.
- Anodic polarization technique reveals that the PS wire immersed in OPC extract can tolerate 100 ppm of chloride only whereas PPC tolerate twice the value.
- It can also be seen from the other electrochemical studies such as LPR technique and Tafel techniques that the corrosion performance of OPC is much better than that of PPC extracts with and without chloride. This could be due to the direct attack of chloride in the aqueous solution state.
- Thus, it can be concluded from all the above experimental investigations that the PS wires embedded in PPC concrete displays better corrosion resistant property than PS wires embedded in OPC concrete.

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