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Corrosion behaviour of prestressing steel in some practical scenarios

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ABSTRACT

There is a tremendous increase in the construction of prestressed concrete (PC) structures worldwide. The most common cause of premature degradation of these structures is the ingress of chlorides through the concrete cover leading to initiation of corrosion of embedded reinforcement. However, there are no clear documentation of the corrosion initiation behaviour of prestressing steel in concrete exposed to chlorides. In this paper, the results of the preliminary investigations done on the pitting characteristics of prestressing (PS) steel in some practical scenarios are discussed. The first set of experiments in alkaline artificial pore solution were aimed at understanding the pitting behaviour of passivated/ corroded PS steel in concrete with and without chlorides. Then, long term experiments (of about 5-month duration) were carried out to assess the effect of supplementary cementitious systems and corrosion inhibitors on the time required for initiation of corrosion in prestressed concrete structures, based on Fick's second law. Totally, 22 specimens of different kinds were tested. This paper highlights some of the salient findings of the investigation.

Keywords: *Prestressing steel; corrosion; service life estimation; supplementary cementitious materials*

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INTRODUCTION

Rapid industrial growth and increasing population in cities throughout the world have led to the need for expansion of transportation networks. A majority of bridges constructed in the recent years are made of prestressed concrete (PC). Alarming bridge failures around the world prove that corrosion of strand and subsequent structural inadequacy can lead to premature failure of PC structures (1-4). Atienza et al. (2012) found that prestressing steel has residual tensile stresses at the surface and compressive residual stresses at the core, due to the drawing process. This adds to the vulnerability of prestressing (PS) steel to corrosion. Corrosion of reinforcement in structures exposed to chloride laden environment is primarily due to the ingress of chlorides through the concrete cover to the level of steel. Increase in concentration of chloride ions at the steel surface beyond a critical level (Cl_{th}), results in the initiation of corrosion. The time required for this (T_i) can be estimated using Fick's 2nd law of diffusion if the chloride concentration at the surface (Cl_s), rate of diffusion of chlorides through the concrete (D_c), and the amount of chlorides necessary to initiate corrosion (Cl_{th}) are known.

The corrosion behaviour of TMT bars has been explored in detail by many researchers and a lot of recommendations are available to concrete mix designers and site engineers for delaying corrosion. However, there is still a lack of clear understanding on the corrosion initiation characteristics of PS steel in concrete. It is surprising to note that strands are even purposefully corroded on site to improve the bond characteristics.

In this study, preliminary investigations were performed to understand chloride induced corrosion initiation in 1) un-corroded steel in un-contaminated concrete 2) un-corroded steel in concrete experiencing chloride-ion diffusion and 3) corroded steel in uncontaminated concrete. For this, a series of tests were conducted in an alkaline solution, which simulates concrete pore solution. Then, linear polarization resistance- based tests were conducted on prestressing steel embedded in cement mortar with 1) ordinary Portland cement (OPC) and OPC with 30% class Fly ash replacement, and 2) No inhibitor, Calcium Nitrite based inhibitor and Bi-polar inhibitor - to detect corrosion initiation. The Cl_{th} was determined and used to estimate the time required for corrosion initiation for all the cases.

EXPERIMENTAL PROCEDURE

King wires extracted from 15.2 mm diameter prestressing (PS) strand were used throughout the study. The composition of the steel is presented in Table 1. The 3-electrode system was adopted for all the tests, where the working electrode (WE) was the PS king wire, counter electrode was either platinum plate (for solution study) or nichrome mesh (mortar study), and reference electrode was saturated calomel electrode (SCE). The details of specimens, test set-up and procedures adopted for each component of the study are explained in the following sections.

Table 1: Chemical composition of the PS steel tested

Elements	Cu	Co	Al	Ni	Mo	Cr	S	P	Mn	Si	C	Fe
Weight (%)	0.02	0.01	0.04	0.02	0	0.27	0	0.06	0.83	0.29	0.84	remaining

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Effect of condition of steel surface and concrete - Solution study

Artificial concrete pore solution (APS) was prepared in the laboratory and used as the electrolyte. The composition of APS is given in Table 2. Twelve-millimeter-long pieces of king wire (3 nos.) were prepared as illustrated in Figure 1.

Table 2 : Composition of artificial concrete pore solution (APS)

Constituents	Quantity (g/l)
Distilled water	966.08
Calcium Hydroxide	0.3
Sodium Hydroxide	10.4
Potassium Hydroxide	23.23

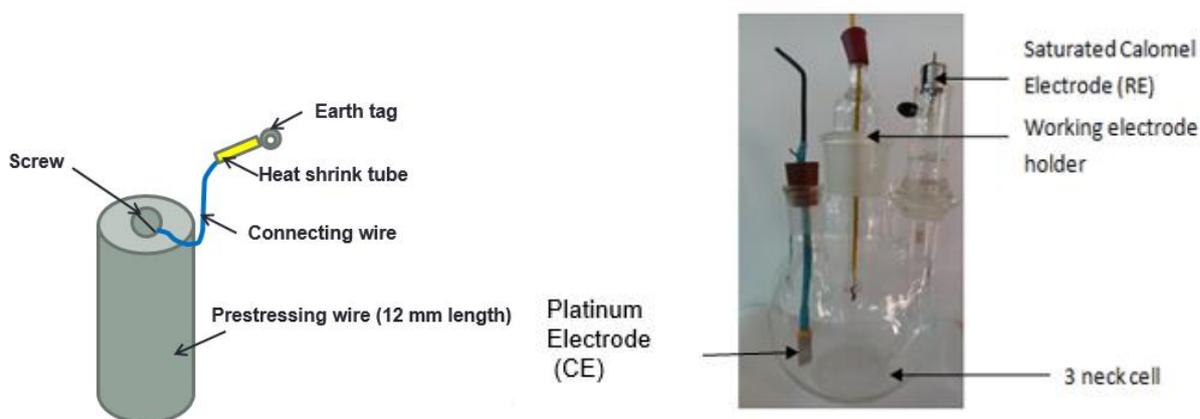


Figure 1: Details of the test set-up and the specimen used in the study

The specimens were pre-conditioned prior to testing. Two specimens were exposed to APS for 12 days and the open circuit potential (OCP) was determined at regular intervals to monitor passivation. The specimens were assumed to have passivated after the OCP values stabilized (constant after 150 hours). The third specimen was kept in the laboratory environment for 12 days, after which the specimen was found to be fully corroded. To simulate the condition of PS in concrete experiencing diffusion of chlorides, one passivated steel specimen was exposed to APS containing increasing proportion of sodium chloride (starting from 0.5%). At each chloride level, LPR test was conducted over a range of $15 \text{ mV} \pm$ the instantaneous OCP. The polarization resistance (R_p) was found for every increment of NaCl dosage. An interval of 120 minutes was maintained between each test for restoration of the specimen, during which the specimens were stored in the same solution. The statistical procedure used by Karuppanasamy et al. (2015) was followed to detect corrosion initiation. The concentration of NaCl in the APS solution at the time of corrosion initiation, was noted.

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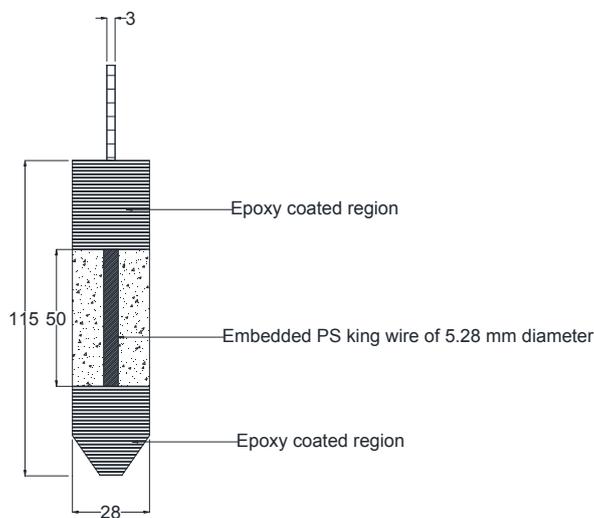
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Cyclic voltammetry test was performed on the preconditioned specimens to understand the pitting characteristics of prestressing steel in uncontaminated, and contaminated concrete containing sufficient chloride ions for corrosion initiation. The OCP was monitored for 60 minutes and the specimens were subjected to a cyclic potential sweep from -40 mV to 1500 mV to -40 mV Vs. instantaneous OCP, at a rate of 5 mV/second.

Influence of supplementary cementitious systems and corrosion inhibitors

Two kinds of corrosion setups were used in this test program. For the determination of Cl_{th} of prestressing steel in various cementitious systems, set-up A (Figure 2 (a)) was used, in which PS king wires were embedded in mortar systems (1:2.75:0.5) containing ordinary Portland cement (OPC) and OPC with 30% Class F fly ash (5 + 5 = 10 specimens). APS containing 3.5% NaCl was used as the electrolyte. The specimens were subjected to wetting and drying cycles in the electrolyte (2 and 5 respectively). LPR test was performed after every wet period over a scan range of $\pm 15mV$ with respect to the open circuit potential.

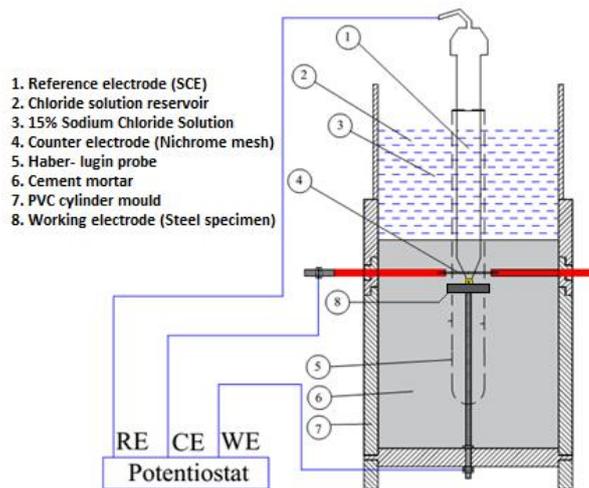
For the determination of Cl_{th} of prestressing steel in various cementitious systems, set-up B (Figure 2(b)) was utilized, in which the mortar systems (1:2.25:0.45) used were 1) OPC (control) 2) OPC with Bio-polar inhibitor (BP-R) and 3) OPC with Calcium Nitrite based inhibitor (CN-R). The inhibitors were added as per the recommended dosage. Totally, 9 specimens were cast (3 in each case). Details on specimen and test procedure can be found in Karuppanasamy et al. (2015).



(a) Set-up A

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(b) Set-up B

Figure 2 : Details of specimens and test set-up

The LPR curve, which is a plot of instantaneous overvoltage against instantaneous current density, was generated during every test and the polarisation resistance R_p was determined. A statistical procedure was followed to detect the corrosion initiation. For the statistical analysis, the plot of $1/R_p$ Vs. duration of exposure was considered. When 5 consecutive values of $1/R_p$ lie within a boundary of $\mu \pm 1.3\sigma$, the system was considered to have stabilised. Following this stable state, if 3 future readings lie above the $(\mu + 3\sigma)$ line, corrosion is said to have initiated (μ - mean; σ - standard deviation). Cl_{th} was determined by analysis of the mortar sample adjacent to the steel. Upon corrosion initiation, the chloride exposure was stopped, and the specimens were autopsied immediately. During autopsy, the specimen was split at the level of steel, and the mortar adjacent to the steel was collected. Figure 3 shows the autopsied test specimen and the sample collection process. The calculation of total chlorides in the cement mortar was done as per the procedure outlined in SHRP S-330 Appendix F. The chloride content (% by weight of cement) was calculated and defined as the chloride threshold of PS steel in that cementitious medium

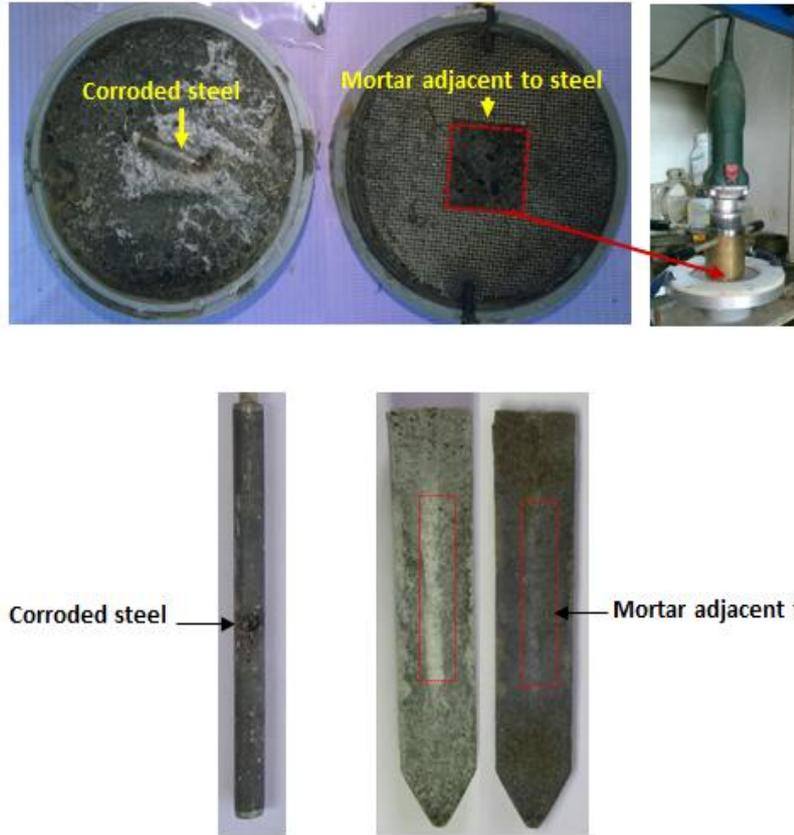


Figure 3: Autopsied test specimen and sample collection process

The determined Cl_{th} values were used as input for estimation of service life based on Fick's 2nd law (Eq 1).

C_d is the cover depth of the assumed PC member. C_s and D_c are the surface chloride concentration and diffusion coefficients respectively. The probabilistic corrosion initiation time was generated for 1000 random realizations, assuming lognormal distribution of the input parameters and T_i . In the analysis, cover depth was assumed to be 64 mm. The diffusion coefficient was assumed to be $7.67 \times 10^{-13} \text{ mm}^2/\text{s}$ for concretes with OPC system, and $3.92 \times 10^{-13} \text{ mm}^2/\text{s}$ for concrete with fly ash, based on the values reported by Sanghoju et al. (2015) for concrete systems with water cement ratio of 0.57. A 10% standard deviation was assumed for the above-mentioned parameters. The obtained Cl_{th} values were used as obtained.

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RESULTS AND DISCUSSION

Effect of condition of steel surface and concrete- solution study

As a part of pre-conditioning, specimens 1 and 2 were passivated in APS for 12 days. Specimen 2 was exposed to APS solutions with increasing NaCl content (from 0.5%). The variation of OCP and $1/R_p$ with the NaCl concentration is shown in Figure 4. It was found that the NaCl concentration required to initiate corrosion in this environment was 3.5%.

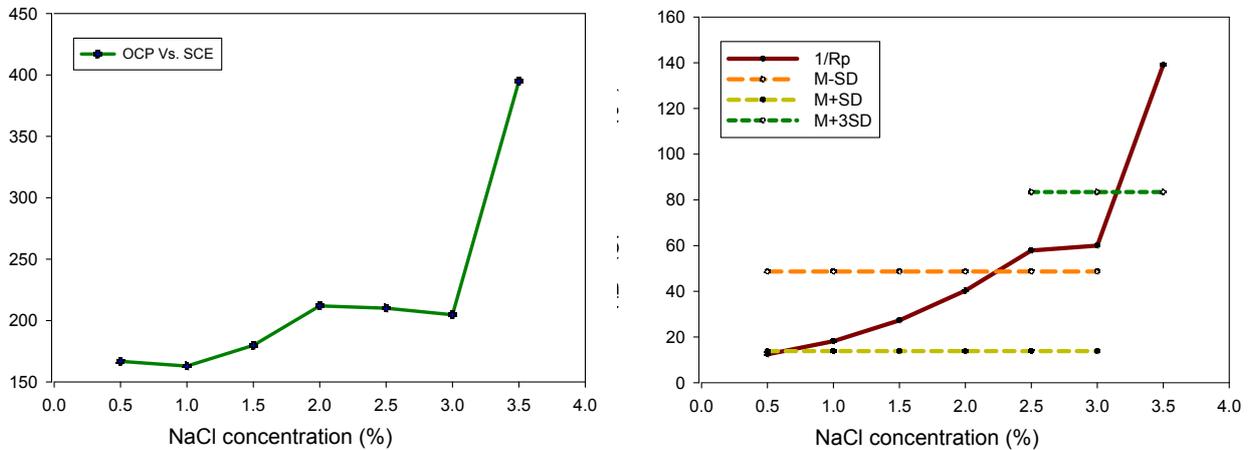
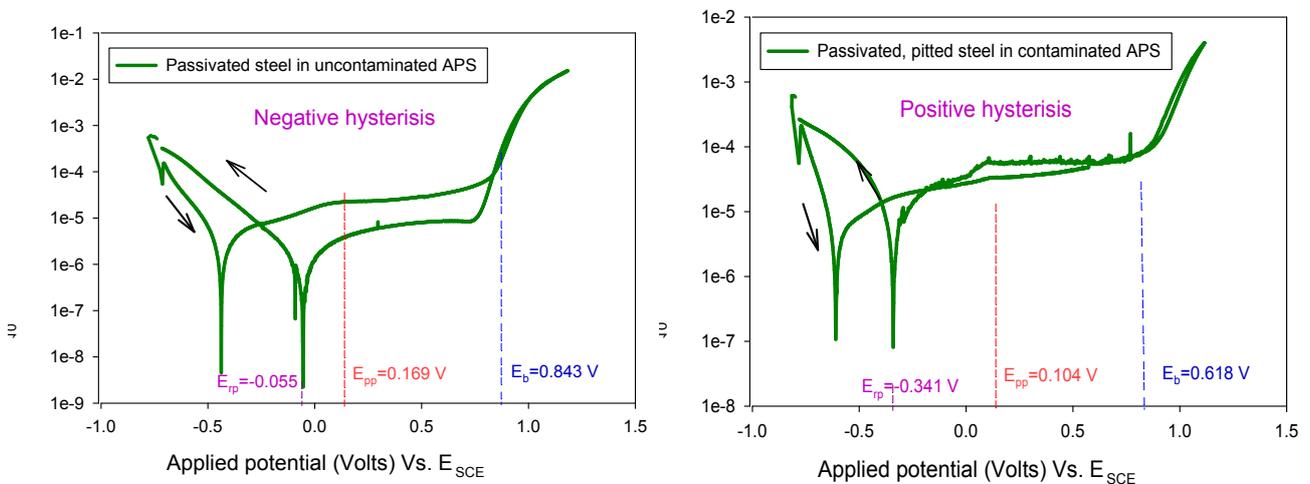


Figure 4 : Variation in OCP and $1/R_p$ with NaCl concentration

PS wire specimens preconditioned to simulate 1) un-corroded steel in un-contaminated concrete 2) un-corroded steel in concrete experiencing chloride-ion diffusion and 3) corroded steel in uncontaminated concrete, were subjected to cyclic potential sweep. The electrolyte for cases 2 and 3 was APS with 3.5 % NaCl. The obtained potential - current density responses are shown in Figure 5.



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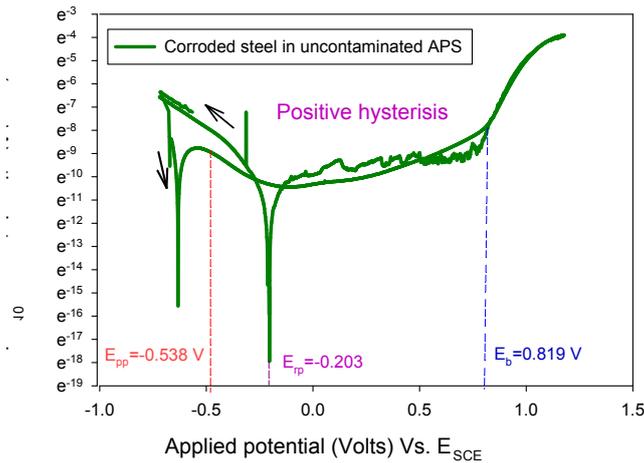


Figure 5 : Cyclic polarization curves for prestressing steel

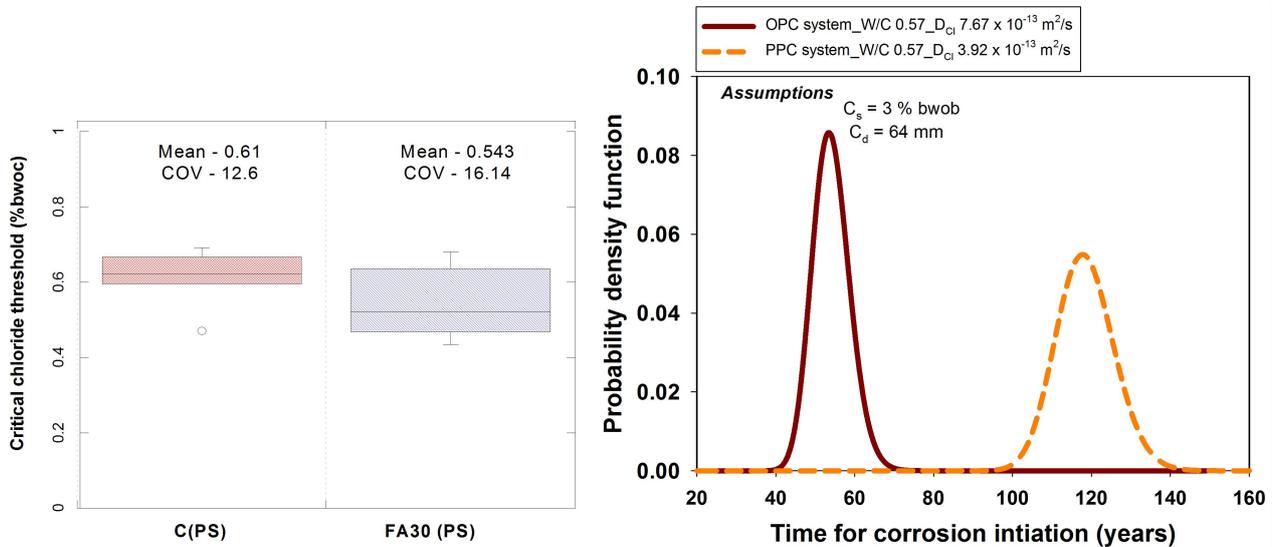
For the passivated steel in uncontaminated APS solution, a negative hysteresis was observed during the backward sweep, which indicates that the passive films formed on the steel are either self repaired or pitting did not occur- the latter may be the case here. The other 2 cases showed positive hysteresis, which means that pitting occurred. Table 3 summarizes the approximate active, passive and transpassive potential regions for prestressing steel subjected to different conditions. Although the corroded PS specimen was exposed to uncontaminated APS, positive hysteresis was observed, which indicates that pitting occurred. But, the passive range was found to be higher for the corroded specimen in contaminated APS, compared to passive and pitted specimens. While this may indicate that the corroded layer is protective in nature, usage of corroded strands in site to improve bond may not still be a good practice, as the cracking of the corroded layer during the stressing operations may expose base steel, leading to early localized corrosion.

Table 3 : Approximate active, passive and transpassive potential regions for prestressing steel

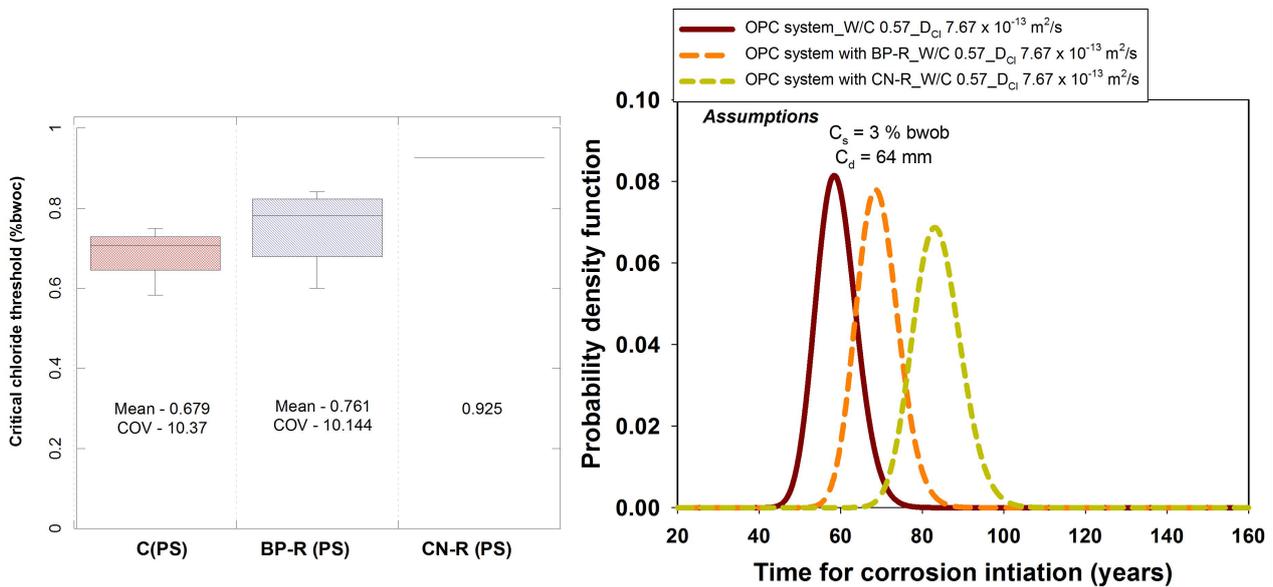
Steel	APS	Active region	Passive region	Transpassive region
Passivated	Uncontaminated	<+0.170 Volts	Between +0.170 and 0.840 Volts	>0.840 Volts
Passivated and pitted	Contaminated with %NaCl = $C_{l_{threshold}}$	<+0.100 Volts	Between +0.100 and +0.620 Volts	>+0.620 Volts
Corroded	Contaminated with %NaCl = $C_{l_{threshold}}$	<-0.538 Volts	Between -0.538 and 0.820 Volts	>+0.820 Volts

Influence of using supplementary cementitious systems

Periodic LPR tests were conducted to determine the Cl_{th} of PS embedded in various cementitious systems. The obtained values of Cl_{th} were used for estimation of T_i as per Fick's 2nd law. The Cl_{th} values and the obtained probability density functions for time for corrosion initiation (T_i) of an arbitrary PC member, are shown in Figure 6.



(a) Cement mortar with and without fly ash



(b) Cement mortar with and without corrosion inhibitor

Figure 6 : Probability density functions for corrosion initiation period (with determined Cl_{th} as input)

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Figure 6 (a) illustrates that although there is no considerable difference in the Cl_{th} of PS with and without the presence of fly ash, T_i is higher for systems with fly ash, such as Portland pozzolana cement (PPC) as pore refinement is achieved and the rate of chloride ingress is slower compared to systems without it. The usage of supplementary cementitious systems would therefore enhance the overall service life of a PC structure.

Figure 6 (b) shows that there is an increase in Cl_{th} of PS steel in concrete containing corrosion inhibitors. In this analysis, the result from only 1 specimen with CN based inhibitor could be used due to the malfunctioning of the specimens during the test. But it seems that the usage of corrosion inhibitors leads to an increase in service life. The changes in transport properties of concrete was not brought into account in this analysis. But, as a previous study done by the author on Calcium Nitrite based inhibitor showed that chloride ion penetration depth was found to decrease with increase in inhibitor dosage, in concrete with similar level of workability (Joseline et al. (2015)), the assumption of same D_{Cl} for systems with corrosion inhibitor may be conservative, but not absurd. However, it should be noted that T_i depends significantly on the input parameters. This case study is for illustrative and comparison purpose only.

OBSERVATIONS AND CONCLUSIONS

Based on the test results, the following observations and conclusions are made:

- It is very important to use concrete and steel of good quality in order to delay the attack of chloride ions to the maximum extent possible. If sufficient built-up of chlorides occur, passivity is affected and pitting occurs inevitably.
- Slight rusting of specimens did not seem to affect the passivation behaviour of steel in the absence of chlorides. It might be protective in nature. But, pitting behaviour was observed. It should also be noted that in real conditions, the strands are stressed to about 0.75 times the ultimate strength of steel. Although not investigated, stressing of corroded strand can lead to cracking of the protective corroded layer, thereby causing early localized corrosion by other mechanisms.
- Based on service life estimation done as per Fick's law, the usage of fly ash in the concrete lead to the delay in the corrosion, due to the decrease in the rate of chloride ingress. Thus, use of supplementary cementitious materials in concrete should be encouraged.
- Use of corrosion inhibitors in concrete results in an increase in corrosion initiation time, if it is assumed that there are no adverse effects on the transport properties.

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