ENHANCING SERVICE LIFE OF PRESTRESSED CONCRETE STRUCTURES BY USING FLY ASH AND CORROSION INHIBITORS

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ENHANCING SERVICE LIFE OF PRESTRESSED CONCRETE STRUCTURES BY USING FLY ASH AND CORROSION INHIBITORS

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Abstract

Seven-wire strands in pretensioned concrete (PTC) structures can undergo chloride-induced localized corrosion. The corrosion products occupy the space between the wires of the strands and do not exert expansive stresses onto the surrounding concrete. Hence, propagation of such corrosion cannot be identified/detected on time using visual observation of concrete surfaces and can lead to catastrophic failure. This scenario necessitates technologies to significantly enhance the chloride-resistance and corrosion-resistance of PTC systems. This paper quantifies the role of pulverised fuel ash (PFA; fly ash) and corrosion inhibiting admixtures (CIAs) in enhancing the probabilistic service life. For this, lollipop specimens with embedded prestressing steel (five in each category) were prepared and subjected to wet-dry exposure using simulated concrete pore solution containing 3.5% NaCl, and the chloride threshold (Cl_{th}) was determined. Also, the synergistic effects of chloride diffusion coefficient (D_{Cl}) and Cl_{th} on the corrosion-free service life of PTC systems are demonstrated. The paper also demonstrates the need for specifying both strength and durability requirements (say, "Mx-Dy" concrete). Such an approach can aid engineers and designers in making informed choices of materials to achieve protection of PTC systems against chloride-induced corrosion and to achieve service life of 100+ years with minimal maintenance/repair cost.

Keywords: Bridge, Chloride threshold, Corrosion, Corrosion inhibitors, Fly ash, Prestressed concrete, Service life.

SYMBOLS AND NOTATIONS

PTC	Pretensioned concrete
SLD	Service-life based design
D_{Cl}	Chloride diffusion coefficient at 28 days
SCMs	Supplementary cementitious materials
PFA	Pulverized fuel ash
Cl_{th}	Critical chloride threshold
PS	Prestressing
RC	Reinforced concrete
CIA	Corrosion inhibiting admixture
hr	High resistivity
lr	Low resistivity
%bwob	% by weight of binder
CE	Counter electrode
WE	Working electrode
RE	Reference electrode
EIS	Electrochemical impedance spectroscopy
S-C	Steel-cementitious
TMT	Thermo-mechanically treated
QST	Quenched and self-tempered
R_p	Polarization resistance
$i_{corr, P\text{-}A}$	Corrosion rate during passive-to-active transition
P_{dep}	Probability of the occurrence of depassivation
x	Travel length of chlorides (say, cover depth, d)
t_{SL}	Design service life
P_o	Target failure probability
Cl_i	Initial chloride concentration
Cl_s	Surface chloride concentration
$erfc()$	Mathematical error function
%bwoc	% by weight of concrete
f_c	Compressive strength of concrete
Mx-Dy	A notation to specify concrete

1. INTRODUCTION

Significant proportion of the world's bridge stock comprises of pre-tensioned concrete (PTC) members, and these important and expensive bridges are expected to be serviceable for a 'deemed-to-satisfy' service life of more than 100 years. However, some of them have started showing signs of premature corrosion-induced distress. Also, because most of the PTC

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Table 1: Condition of corroded PTC structures at various stages of corrosion detection

NAME AND LOCATION OF BRIDGE (REFERENCE)	STAGE OF DETECTION	OBSERVATION UPON DETAILED INVESTIGATION	CONSEQUENCE (AGE AT THE TIME OF DETECTION, YEARS)
Boundary Creek Bridge, New Zealand [1]	Cracking	• Localized wire breakage • Hidden corrosion	Strand removal (≈ 48)
Tiwai Point Bridge, New Zealand [1]	Cracking	• Up to 60% estimated section loss • Hidden corrosion	Decommissioning (≈ 40)
Hamanatua Stream Bridge, New Zealand [2]	Spalling	• Up to 10% estimated section loss • Hidden corrosion	Significant repair (≈ 38)
Lowe's Motor Speedway Pedestrian Bridge, North Carolina [3]	Collapse	• Pre-mixed Calcium Chloride set accelerator • Hidden corrosion	Human injury (≈ 5)

bridges are young (say, couple of decades old), their long-term performance issues are not yet widely reported. Some well-documented cases of corrosion-induced premature failure of PTC members in bridges are presented in Table 1. As given, the consequences of corrosion of PTC girders in New Zealand were severe with significant repair and decommissioning in about 40 years of age. Although the corrosion-induced collapse of the bridge in North Carolina at five years of age was due to pre-mixed calcium chloride accelerator, which is an extreme case, the incident provides an indication on the possible brittle/catastrophic failure mode and high risk/safety concerns.

In case of conventional steel rebars, the corrosion products start exerting expansive stresses onto the surrounding concrete when the thickness of the rust layer reaches about 15 μm [4], leading to cracking/spalling etc. (depending on the pore structure of cover concrete). The corrosion products ooze out and reach the concrete surface causing brown stains, which is usually considered as a sign of corrosion by the inspectors. However, the case with corrosion of the seven-wire prestressed steel strands is different. The corrosion products fill the interstitial spaces between the wires [as shown in Figure 1(a)] prior to exerting pressure on the surrounding concrete and cracking it. Therefore, visible signs of strand corrosion will not be observed on the concrete surface at least upto about 6% cross-sectional loss – making timely detection of corrosion challenging [5,6].

Also, if the flow of corrosion along the length of the interstitial spaces (in the direction of strands) is considered, the critical loss in cross-section could be much more than 6%. This is evident from the significant cross-sectional loss shown in Figure 1(b), in which case no surface stains were observed. Strand breakage is also a recurrent observation from PTC structures that have failed much before the expected service life; and that too without any corrosion stains on the concrete surface [as shown in Figure 1(c)]. Therefore, if interventions are not made before the strand corrodes, the load carrying capacity can reduce significantly because of the vicious series of wire breakage → stress redistribution → strand breakage, resulting in catastrophic failures [1,3,7–9]. According to fib Bulletin 26, over 40% of failures in PTC can be attributed to unsatisfactory corrosion protection or error in construction [10].

2. SERVICE-LIFE BASED DESIGN (SLD) OF PTC

Uncontaminated concrete cover provides a physical barrier against ingress of corrosive species and also the alkaline chemical environment (pH ≈ 13) for passivation of embedded steel [11]. The passive film is believed to be a protective oxide or hydroxide film that reduces the rate of dissolution of steel to negligible ranges [12–14]. Once the passive film breaks down, active corrosion of steel bars begins and the corrosion products, being expansive, can cause cracking and then further

Note: Arrows indicate severe section loss

(a) Interstitial spaces filled with corrosion products prior to exerting pressure onto the surrounding concrete (adapted from [5])

(b) Severe localized hidden corrosion and section loss observed on prestressed wires in a 40 year old bridge (adapted from [1])

(c) The soffit of a 50 year old bridge girders showing strand breakage due to corrosion (adapted from [1])

Figure 1: Insidious and hidden nature of strand corrosion in PTC systems

deterioration[15]. Service-life based design (SLD) is an approach to avoid deterioration due to environmental loads until the end of design life[16].

2.1 Choice of materials

A traditional prescriptive or deemed-to-satisfy approach[16], for selection of concrete for any particular application, imposes requirements on parameters such as concrete cover, compressive strength at 28 days, cement content, water-cement ratio, maximum chloride content in cement, etc.[17–22] for various exposure classes. Although simple and convenient, this approach fails to provide guarantee/verification of the potential durability. The recent global shift towards performance-based specifications for concrete cover[23,24] emphasizes on providing limits on quantifiable transport properties of concrete such as chloride diffusion coefficient (D_{Cl}) , oxygen permeability, water permeability, etc. This paves way for a wider choice of materials for the consideration in SLD of PTC. Concretes with supplementary cementitious materials (SCMs) such as pulverized fuel ash (PFA), ground granulated blast furnace slag (GGBFS), silica fume and ternary blends (say, limestone calcined clay cement [LC^3]) are promising alternatives owing to the refinement of pore structure and lowering of D_{Cl}[25–28].

In addition, direct measures for corrosion protection of reinforcement are also used for important structures based on the "avoidance of deterioration" approach[16]. Use of non- or less-reactive reinforcement, separation of reactants, and electrochemical suppression of corrosion reactions fall in this category (e.g., use of stainless-steel strands and epoxy-coated strands, and corrosion inhibiting admixtures [CIAs])[29]. The role of CIAs on the Cl_{th} (which is within the scope of the present study) is unknown and may vary depending on the corrosion protection mechanism of the CIA and their effects on transport properties of concrete, which needs to be studied. Also, the characteristics of PS such as chemical composition, surface stress state, surface microstructure etc. can have a bearing on the initiation of corrosion as per unpublished work at IIT Madras.

The remaining paper is organized in the following manner. First, the significance of the present work to the civil engineering profession at large is discussed. Then, the characteristic surface features of PS steel, and the need for specifying the surface characteristics are discussed. Following this, the experimental work on determining the Cl_{th} of PS steel and the role of PFA and CIAs in delaying the initiation of corrosion is presented. Then, a case study on the service life of a typical PTC girder with various cementitious systems is presented and the synergistic effect of Cl_{th} and D_{Cl} is demonstrated. Finally, the importance of specifying "Mx-Dy concrete" as a way forward for achieving target service life has been emphasized.

3. RESEARCH SIGNIFICANCE

Unlike reinforced concrete systems with rebars, the PTC systems with strands do not show any signs of corrosion at the concrete surface until it is too late. Because of the potential catastrophic failure, the corrosion of strands must be prevented from initiating. The corrosion experiments, service life analysis procedures, and the method of specifying concretes presented in this paper can help engineers to select the right materials and systems to achieve the desired corrosion-free service life for PTC structures.

4. EXPERIMENTAL PROGRAM

4.1 Materials

All the seven-wires of a strand are manufactured from the same parent steel rod and are drawn using similar method prior to stranding. Therefore, the king (central) wire of 5.28 mm diameter, extracted from PS steel strands of nominal diameter 15.2 mm, were used in the corrosion studies. For understanding the variability in the characteristics of PS steel conforming to different specifications (namely IS 14268[30], prEN10138[31] and ASTM A416[32]), PS steel samples were collected from USA and Germany for characterization. The chemical composition of the three PS steel strands as determined using Metavision 108 NN+ emission spectrometer is given in Table 2. Table 3 provides

Table 2: Composition of prestressing steels used in this study

ELEMENT	CONCENTRATION (wt. %)		
	INDIA 1 (I1)	GERMANY 1 (G1)	USA 1 (U1)
C	0.900	0.760	0.830
Si	0.194	0.093	0.240
Mn	0.716	1.464	0.780
P	< 0.005	0.014	0.005
S	0.014	0.024	0.010
Cr	0.560	2.600	0.030
Ni	0.093	5.320	0.060
Cu	0.025	0.337	0.120
Al	0.032	0.044	0.001
Mg	< 0.005	0.008	0.012
Nb	0.052	0.281	0.030
Sn	0.039	0.124	0.005
Ti	0.055	0.300	0.002
V	0.038	0.970	0.077
N	0.011	0.025	0.0195
Fe & TE	Remaining*		

* TE-Trace Elements

Table 3: Oxide composition of cementitious materials used in this study

OXIDE	CONCENTRATION (wt. %)	
	ORDINARY PORTLAND CEMENT	CLASS F FLY ASH
CaO	64.6	1.3
SiO_2	19.0	59.3
Al_2O_3	4.2	29.9
Fe_2O_3	3.9	4.3
MgO	0.9	0.6
Na_2O	0.2	0.2
K_2O	0.6	1.4
TiO_2	0.2	-
SO_3	1.7	0.2
LOI	1.4	-

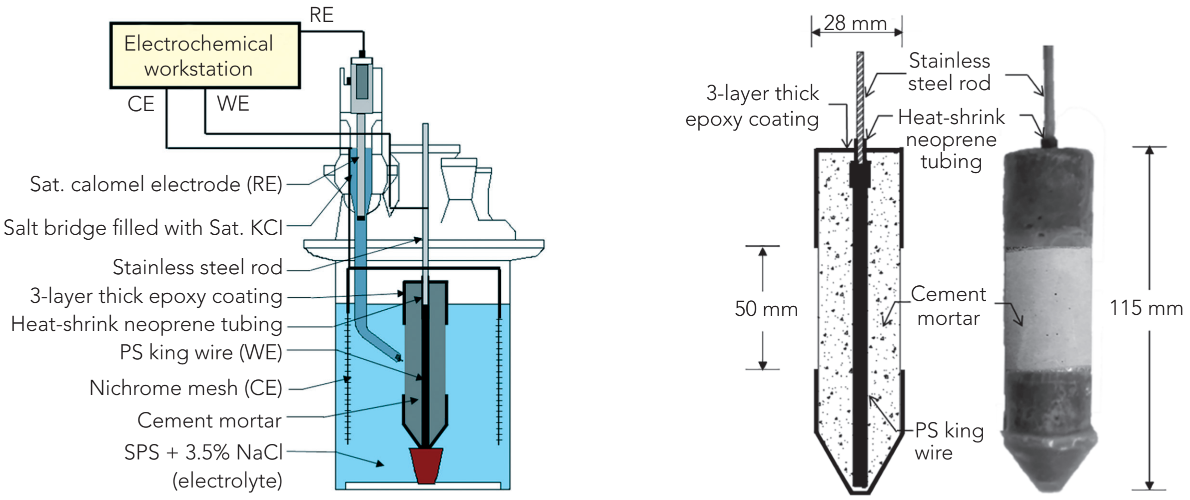
the oxide composition of Ordinary Portland Cement (OPC) and PFA used in the mortar for preparing the corrosion test specimens. Four cement mortars with a mix ratio of 0.5:1:2.75 (water: binder: fine aggregate) were used; namely OPC, PFA30, OPC_CIA-hr and OPC_CIA-lr. In the three OPC mixes, 100% of the binder component consisted of OPC; in the PFA30 mix, 30% of OPC was replaced with PFA by weight. The OPC_CIA-hr and OPC_CIA-lr mixes contain commercially available CIAs admixed at the recommended dosage as per manufacturer [0.8% and 4.8% by weight of binder (%bwob), respectively]. The suffix 'hr' stands for high resistivity and indicates that the CIA has a dual mechanism of action with promised pore blocking in addition to slowing down the rate of corrosion. The suffix 'lr' stands for low resistivity and indicates that the CIA does not possess any pore blocking or refining capabilities. The fine aggregate component consisted of a 50:50 mix of standard sand (of particle sizes 1 to 0.5 mm and 0.5 to 0.09 mm, conforming to IS 650 [33]) to ensure adequate gradation and packing. Distilled water was used for the preparation of the corrosion test specimens and test solutions.

4.2 Characterization of PS conforming to different specifications

The surface of 10 mm long PS steel samples from India, Germany and USA were characterized using X-ray diffraction (XRD) to determine the surface residual stresses, and Scanning electron microscopy with Energy dispersive X-ray analysis (SEM/EDAX) to study the surface characteristics. This was done to understand the similarities and differences among PS steel conforming to different specifications in different countries. The chemical composition of these three steels (see Table 2) were also compared.

4.3 Chloride threshold of PS steel in various cementitious systems

Lollipop specimens with embedded PS steel wires were used in this study. Details on the test setup and specimen are shown in Figure 2. PS steel king wire samples of 100 mm length were cut using an abrasive cutter (with continuous supply of coolant). Then, they were drilled and taped on one side to connect a stainless steel (SS) rod of 3 mm diameter. The prepared steel samples were ultrasonically cleaned in distilled water for 15 minutes and wiped with a cloth soaked with ethanol. The SS rods were then threaded onto the steel wire and junction was covered with heat-shrink, neoprene tubing and placed in the plastic tube mould. After casting and demoulding, the lollipop specimens were sealed at the bottom using epoxy and cured for



(a) Schematic of the test setup

(b) Lollipop specimen

Figure 2: Test setup and lollipop specimens used to determine Cl_{th} of PS

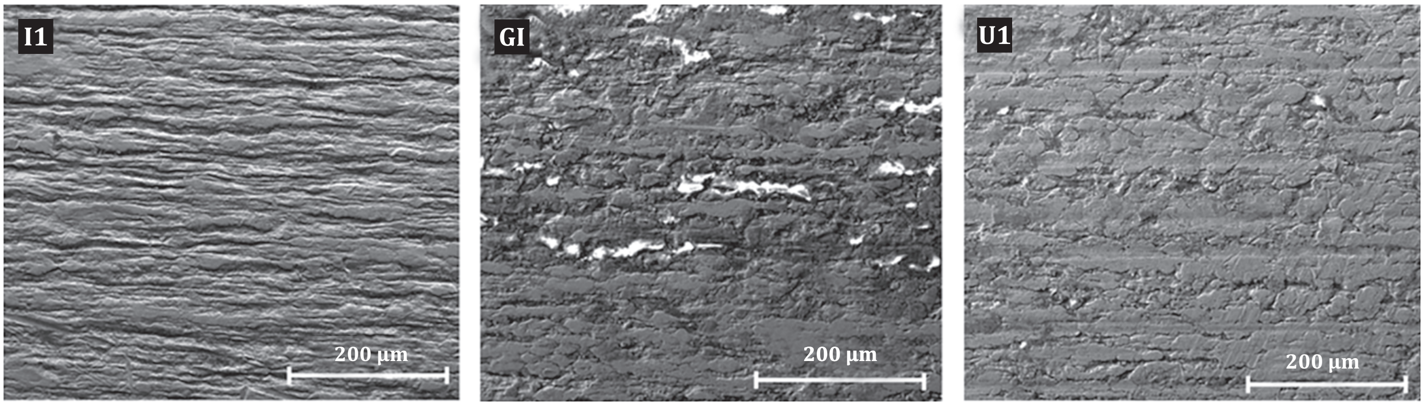
28 days in a curing chamber. Five lollipop specimens each were prepared with the four cementitious binder systems considered (i.e., OPC, PFA30, OPC_CIA-hr and OPC_CIA-lr). The cured specimens were dried for 5 days, during which mortar surface (except a 50 mm-long region in the middle) was coated with epoxy, as shown in Figure 2(b).

The specimens were then exposed to dry-wet cycles (5 days of dry period followed by 2 days of wet/immersion period, respectively) using simulated pore solution, SPS, (with 0.3 g $Ca(OH)_2$ + 10.4 g NaOH + 23.2 KOH and 967 g H_2O per litre of solution) containing 3.5% NaCl. The composition of the simulated pore solution has been kept consistent with past studies in the laboratory and literature. The principle behind the assumed composition is that a presence of adequate Ca, Na and K ions is ensured, and the resultant solution has a pH of 14, thereby simulating a general concrete pore solution. Circumferentially placed nichrome mesh was the counter electrode (CE), the PS king wire was the working electrode (WE), and the saturated calomel electrode was the reference electrode, RE (placed in between CE and WE). Half-cell potential and electrochemical impedance spectroscopy (EIS) techniques were used to obtain the corrosion potential and resistance to polarization (R_p) during each wet period. Then, corrosion potential and $1/R_p$ were monitored to detect the initiation of corrosion. For the EIS tests, an AC signal of ±10 mV amplitude was applied over a frequency range of 10^5 – 0.01 Hz without any DC overpotential (as recommended by Rengaraju [34]). After the detection of corrosion initiation, the specimens were autopsied and the acid-soluble chloride content at the level of steel was determined as per SHRP S330 [35] and was defined as the Cl_{th} of PS steel embedded in the respective cementitious binder system.

5. RESULTS AND DISCUSSIONS

5.1 Characterization of PS steels conforming to different specifications

As shown in Table 2, a large variation in the concentration of elements contributing to resistance to corrosion such as Cr, P, Nb, Ti and N was observed among the 3 steels. This is because most of the standards specify mechanical properties (say, strength criteria) and the means for attaining them is left to manufacturer [36]. Also, ASTM A416, A882, A886 and A910, etc. do not specify required chemical composition of the strand and the manufacturer is free to adjust them as necessary to meet the mechanical requirements [29]. The differences in the surface characteristics (obtained using SEM and XRD techniques) among the PS steel samples from India, Germany and USA (I1, G1, and U1, respectively) are shown in Figure 3. The roughness of the three steels was found to be different – with the Indian steel rougher than the others. In another study, the line and surface roughness of the Indian PS steel, as determined by laser microscopy, was found to be 1.5 to 2 times more than that of PS steel sourced from Germany [37]. The surface roughness is reported to have adverse effects on the pitting resistance [38]. Also, it is found that the stress state at the time of passivation can have an effect on the resistance of passive film against chloride-induced deterioration with tensile residual stress being detrimental and compressive residual stress being protective in nature (another unpublished work at IIT Madras). The PS steel is expected to have tensile residual stress at the surface due to the cold drawing processes [39]. However, low-relaxation strands generally undergo heat treatment, where the surface stresses are relieved. The PS steels I1 and G1 were still found to have residual tensile stresses at the surface while PS steel U1 had residual compressive stresses (although low in magnitude).



σ = +68.2 ± 14.1 MPa
τ = –5.4 ± 6.4 MPa

σ = +174.0 ± 19.1 MPa
τ = +1.2 ± 8.6 MPa

σ = –27.5 ± 12.2 MPa
τ = +3.9 ± 5.5 MPa

Note : 1) σ and τ stand for longitudinal and shear stresses, respectively.
2) Sign convention: Tensile (+), Compressive (–)

Figure 3: Surface characteristics of PS steels from India, Germany, and USA

These variations in the composition and surface characteristics among PS steels could lead to differences in their corrosion performance. Currently, other than mechanical requirements, the limiting values for both sulphur content and phosphorous content are provided as 0.04% in IS:14268 (2017) [30]. It is recommended to include specific clauses on upper and lower limits of concentrations of elements (such as Cr, P, Nb, Ti, and N), surface roughness, and residual stress in IS: 14268 (2017) [30].

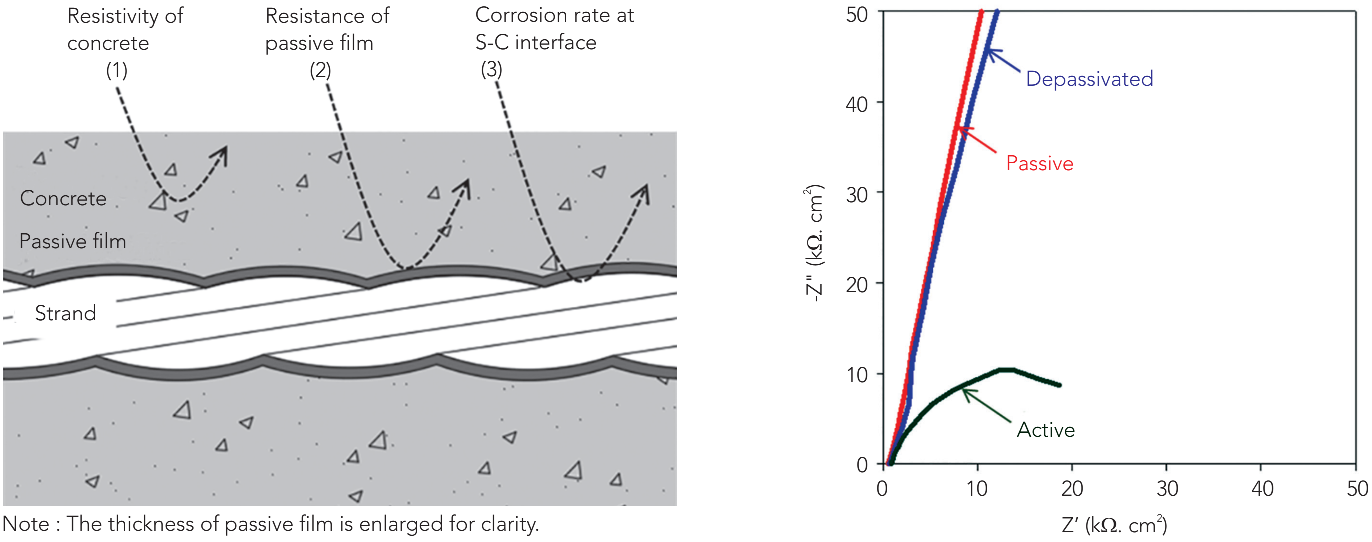
5.2 Strategy to delay corrosion initiation

Figure 4(a) shows the multi-level protection strategy for PTC structures to delay the onset of corrosion in embedded strands. The concrete cover is the first barrier against initiation of corrosion of embedded steels. Once chlorides reach the surface of the steel, the passive film acts as a second barrier by providing further protection. The resistance of passive film against chloride-induced breakdown can depend on multiple factors such as the surface characteristics, composition of steel, passivating environment, [38,40,41]. After the passive film is locally damaged due to the action of sufficient amount of chlorides (Cl_{th}), the initiation of corrosion of the exposed steel surface depends on the microclimate in the steel-cementitious (S-C) interface (i.e., oxygen and moisture concentrations, pH, etc. at the surface of the exposed steel). Therefore, the S-C interface can be considered as the third barrier, whose protectiveness can depend on the rate of corrosion during passive-to-active transition ($i_{corr,\ P\text{-}A}$). While D_{Cl} can provide an indication of the effectiveness of the concrete cover (first barrier), the Cl_{th} determined at the initiation of the active stage can quantify the effectiveness of the protection offered by passive film and S-C interface (second and third barriers), in this sequence.

In addition to the corrosion resistance of the PS strand, the materials used in the concrete influence the effectiveness of each level of protection against corrosion of PTC systems. The choice of materials should be such that the synergistic protective effect of the three barriers shall ensure corrosion-free condition throughout the desired service life. In this study, the passive-to-active transition of PS steel during progressive exposure to chlorides (by dry-wet cycles) was monitored using electrochemical measurements. A typical evolution of impedance response until the initiation of corrosion in PS steel is shown in Figure 4(b). The large difference in the pattern of the impedance response (between blue and green curves) indicates a drastic transition of the PS steel from 'passive' state to 'active' state of corrosion. This is attributed to the cracking of the passive film after depassivation. It should be noted that this is unlike the passive-to-active transition in case of Thermo-Mechanically Treated (TMT) rebars, which experience pitting corrosion after chloride-induced depassivation with other regions of passive film intact. This difference in the mechanism of PS and TMT steels is attributed to the chemistry, residual surface stress state (compressive in TMT and tensile in PS steels) and the surface microstructure (another unpublished work at IIT Madras). Note that the technically correct name for TMT steel is quenched and self-tempered (QST) steel.

5.3 Chloride threshold of PS steel in various cementitious systems

The EIS response was obtained from the lollipop specimens with ≈10 mm thick mortar cover around the PS steel wire, at each test cycle. The spectra were analysed using the equivalent electrical circuit suggested by Rengaraju *et al.* [42] and the polarization resistance (R_p), which is indicative of the corrosion state of the



(a) Longitudinal cross-section of a strand concrete systems showing multi-level protection against corrosion

(b) Typical impedance spectra showing passive-to-active transition of PS steel in mortar and exposed to chlorides

Figure 4: Corrosion protection mechanisms and electrochemical response from strand-concrete systems

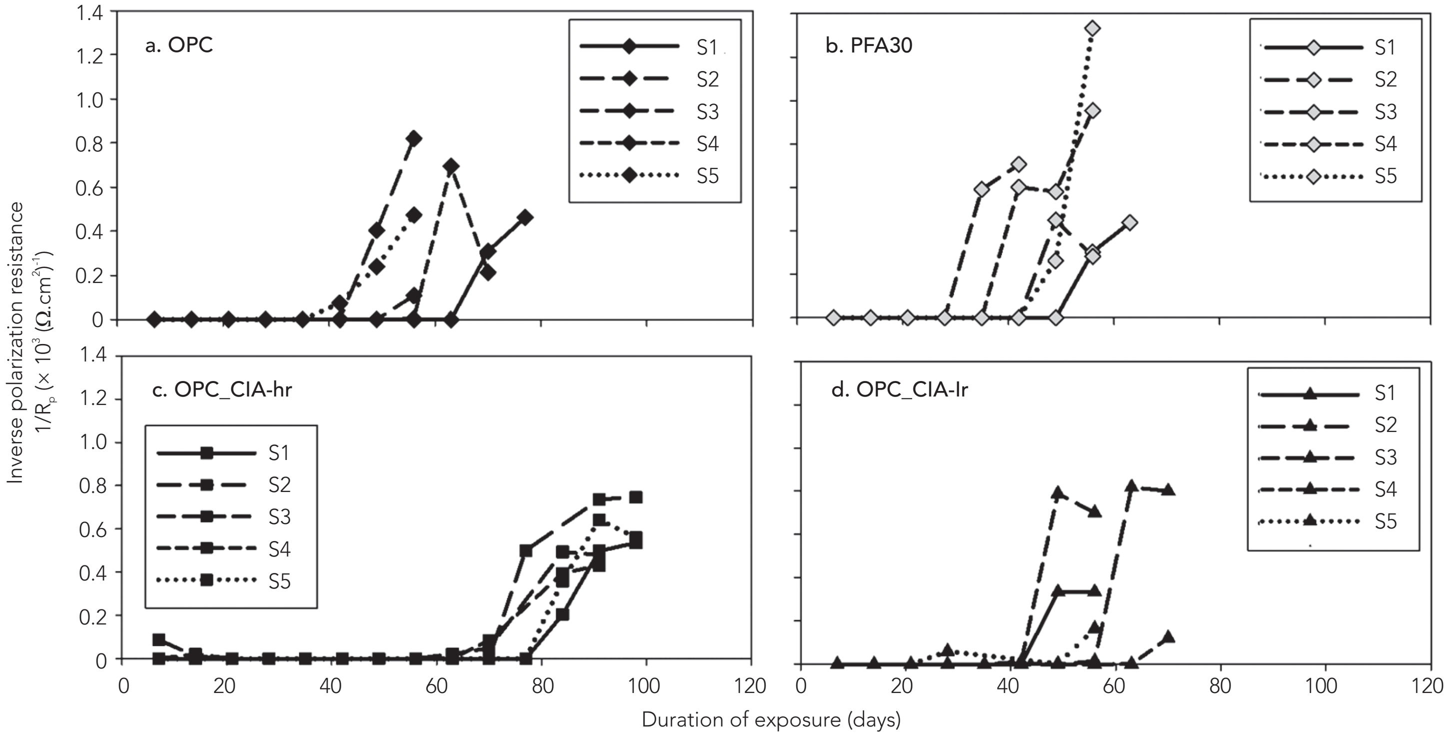
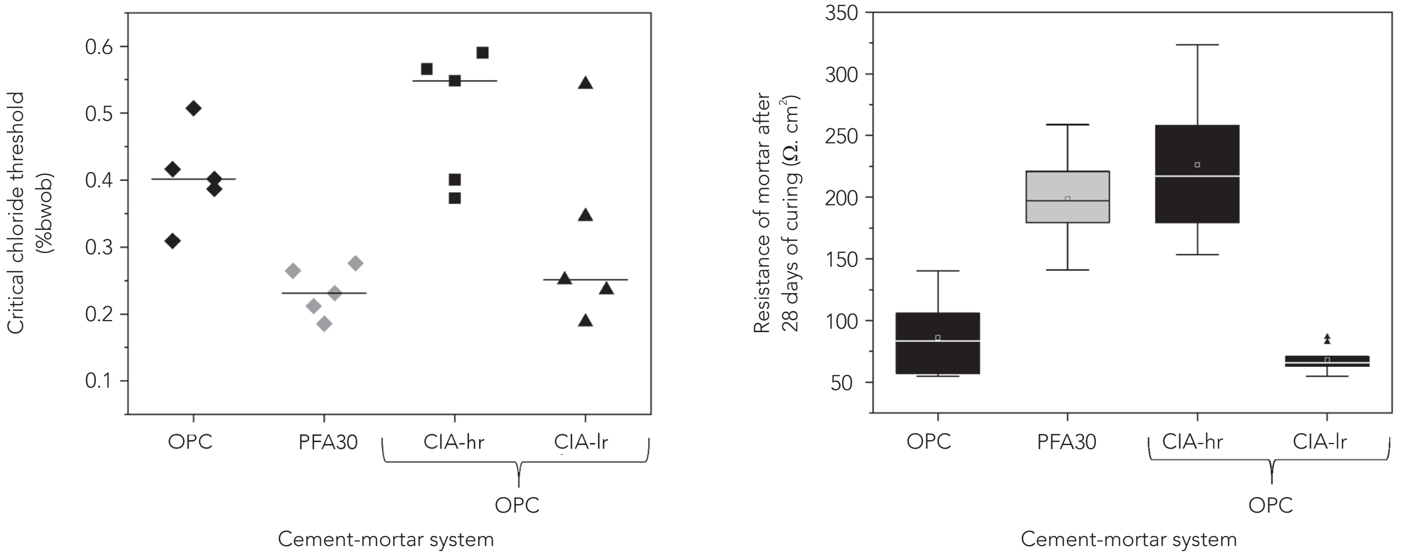


Figure 5: Variation in 1/Rp of PS steels embedded in various cementitious systems subjected to dry-wet chloride exposure

steel, was determined. The variation in inverse polarization resistance ($1/R_p$) with exposure to chlorides, for the four systems studied, is shown in Figure 5 . In these, the significant increase in $1/R_p$ indicates the corrosion initiation of the particular test specimen. Notice that the OPC, PFA30, and OPC_CIA-lr systems exhibited corrosion initiation at similar range of time (in between 40 and 60 days of exposure); whereas the OCP_CIA-hr systems exhibited corrosion initiation after 60 days.

Following the detection of corrosion initiation, the specimens were autopsied at the level of steel (split longitudinally into halves) and less than 1 mm deep layer of the mortar adjacent to the steel was extracted using a metallic round file (5 mm diameter) and tested for the acid soluble chloride concentrations as per the guidelines prescribed in SHRP S330 [35]. This chloride concentration is defined as the Cl_{th}. Figure 6(a) shows the obtained Cl_{th} values for the 20 specimens (5 specimens



(a) Chloride threshold of unstressed prestressing steel in various mortars

(b) Chloride threshold of unstressed prestressing steel in various mortars

Figure 6: Indicators of resistance against chloride-induced corrosion initiation

for each case). The average Cl_{th} was found to decrease in this order: OPC_CIA-hr > OPC > OPC_CIA-lr > PFA30. The Cl_{th} of PS steel in PFA30 was found to be lower than that in OPC system. This can be due to the lower alkalinity of the passivating environment in PFA30 due to the consumption of $Ca(OH)_2$ during the pozzolanic reactions. A lower pH is reported to have adverse effects on the corrosion resistance of QST and high strength stainless steels with potential use as PS strand reinforcement [25,43]. The Cl_{th} of PS steel in OPC_CIA-hr was found to be higher than that of PS steel in plain OPC system; whereas the Cl_{th} of PS steel in OPC_CIA-lr systems exhibited less Cl_{th} than that in OPC systems.

The resistance of the mortar cover of each system after 28 days of curing, as extracted from the corresponding bulk EIS spectra (the high-frequency intercept of Z'-Z'' response), is shown in Figure 6(b). The average resistance of OPC was higher than that of OPC_CIA-lr and lower than that of OPC_CIA-hr. This trend matches with that of Cl_{th} indicating that the resistance, and hence the resistivity of the mortar can affect Cl_{th}. This could be due to the change in microclimate at the S-C interface because of the pore refinement and the chemistry of the CIAs (which is not usually disclosed by the manufacturer). It should also be noted that all CIAs need not always have positive effects on the Cl_{th} and should be thoroughly tested for their eventual effect on service life in the respective PTC systems - prior to their usage in anticipation of enhanced service life. This can be done by meeting the ASTM C1582 [44] specifications and assessing the Cl_{th} and checking if the use of CIAs help meet the target service life. On the other hand, the resistivity of PFA30 mortar was found to be higher than that of OPC mortar [see Figure 6(b)]. This is reflected in the variation in $1/R_p$ and Cl_{th}. Although the PFA30 system exhibited lowest Cl_{th}, the number of dry-wet cycles up to point of initiation of corrosion was found to be similar to that of OPC. This indicates the synergistic effects of D_{Cl} of concrete and Cl_{th} of steel-cementitious system on the time to initiation of corrosion. Authors recommend that one should not choose a cementitious binder system purely based on Cl_{th} values and the synergistic effects of D_{Cl} and Cl_{th} on service life must be considered. Also, the corrosion inhibitors with detrimental effects on the resistivity of concrete should not be recommended.

6. GUIDELINES FOR MATERIAL SELECTION

6.1 Choice of limit state for service-life based design of PTC structures

The fib Bulletin 34 presents guidelines for the service-life based design of RC and PTC structures considering any one of the following four limit states: 1) Depassivation of steel reinforcement; 2) Cracking of cover concrete; 3) Spalling of concrete cover and 4) Structural failure through bond failure or reduction in the cross-sectional area of the strand [16]. Figure 7 shows a comparison of the level of deterioration of systems with TMT/QST steel rebars and PS steel strands at various limit states.

In case of RC structures, the engineers get sufficient time to intervene and save the structure even after corrosion propagates to significant levels (say, from Stage 2R to 4R). However, this is not the case in PTC systems. As explained earlier, the progress of corrosion is hidden in prestressed concrete systems with multi-wire strands. Therefore, by the time cracking is observed on the concrete surface, a significant localised corrosion would have happened (2S). Following this, localized corrosion and

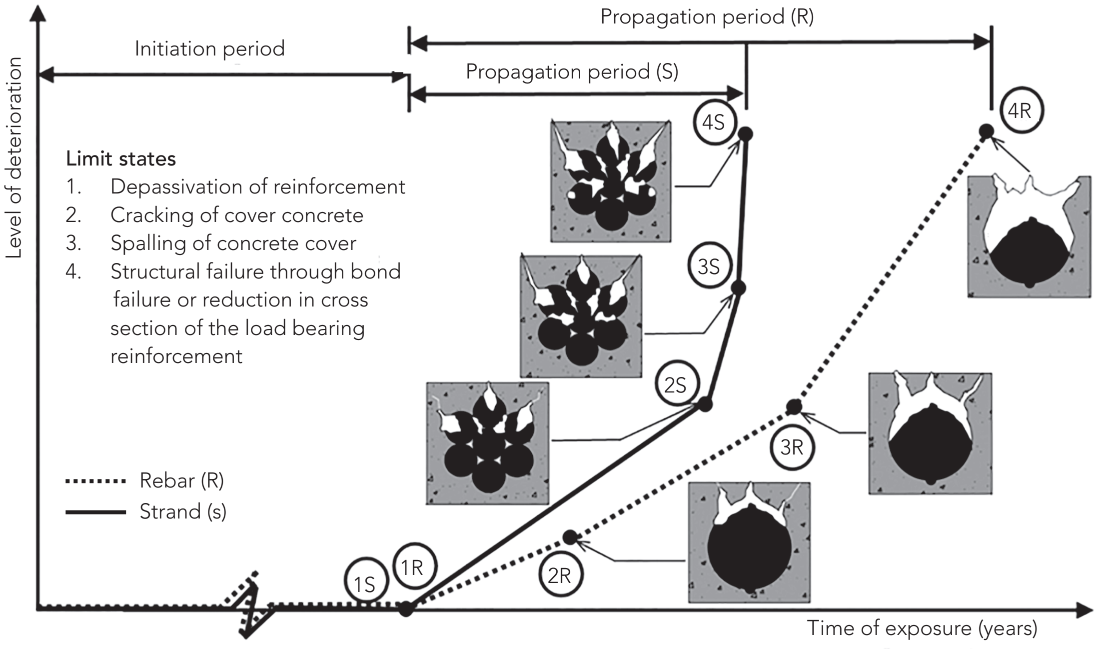


Figure 7: Stages of reinforcement corrosion and definition of limit states for service-life design of RC and PTC systems (partly adapted from fib [16])

wire breakage can occur leading to spalling of concrete and structural failure, within relatively short period of time – making it difficult to intervene between the Stages 2S, 3S and 4S. In fact, strand failure can happen even before reaching the Stage 2S[1]. Hence, designing for depassivation limit state is critical for PTC structures.

The fib Bulletin 34 rightly recommends considering the depassivation of strands as ultimate limit state in the reliability-based design, while that in rebars is a serviceability limit state[16]. The depassivation limit state function for fully probabilistic design of PTC systems can be as follows [Equation (1)][16].

$$P_{dep.} = \mathrm{P}\,\{Cl_{th} - Cl\,(\mathrm{d}, t_{SL}) < 0\} < \mathrm{P}_0 \tag{1}$$

where, $P_{dep.}$ is the probability of the occurrence of depassivation; Cl_{th} is the chloride threshold; *d* is the depth of concrete cover; t_{SL} is the design service life; *Cl* (*d*, t_{SL}) is the chloride content at depth *d* and time t_{SL}; and P_0 is the target probability of failure. By substituting the non-steady state chloride diffusion coefficient (D_{Cl}) of concrete in the Fick's 2nd Law of diffusion and equating the travel length of chlorides, *x* to clear cover depth of strand, one can estimate t_{SL}, which is the time (*t*) at which the chloride concentration at the strand surface reaches Cl_{th}. This is expressed in Equation (2).

$$Cl\,(x,t) = Cl_i + Cl_s - Cl_i\, erfc\left(\frac{\mathrm{x}}{\sqrt{4.\,D_{Cl}.\mathrm{t}}}\right) \tag{2}$$

where, Cl_i is the initial chloride concentration, Cl_s is the surface chloride concentration and *erfc* () is the mathematical error function.

6.2 Comparison of service life of various PTC systems

To illustrate the synergistic effects of D_{Cl} and Cl_{th} on the service life of various PTC systems, four concretes with different D_{Cl} were considered for a case study. The 28-day D_{Cl} of some common concrete mixes are presented in Table 4. It can be observed

Table 4: Chloride diffusion coefficient (D_{Cl}) of common concrete mixes (Joseline *et al.*[47], Pillai *et al.*[25], and other unpublished work at IIT Madras)

SCM CONTENT	TOTAL BINDER CONTENT (kg/m^3)	w/b	28-DAY COMPRESSIVE STRENGTH (N/mm^2)	28-DAY CHLORIDE DIFFUSION COEFFICIENT, D_{Cl} (x10^{-11} m^2/s)
0	310	0.6	32.4	1.49
15% Slag A			36.0	1.64
20% Slag B + 20% Class F fly ash		0.5	38.3	0.73
LC3			38.8	0.33
0			45.4	1.87
15% Slag A	340	0.55	36.0	1.15
15% Slag B			44.5	1.06
30% Class F Fly ash	360	0.45	37.6	0.35
LC3			40.7	0.13
50% Slag C	400	0.35	≈ 40	0.07
47% Slag C+3% Microslag			≈ 40	0.066
46% Slag C+ 4% Microslag			≈ 40	0.033
45% Slag C+ 5% Microslag			≈ 40	0.012
40% Slag C+10% Microslag			≈ 40	0.022
47% Slag C+3% Silica fume			≈ 40	0.035
0	310	0.5	43.8	1.44
15% Slag A			44.7	1.07
15% Slag B			49.2	1.8
30% Slag B			44.7	1.34
0	340	0.55	42.9	1.17
LC3		0.4	56.7	0.17
0	360		60.0	1.56
30% Class F Fly ash	380	0.35	54.6	0.19

that concretes belonging to similar strength grades need not exhibit similar D_{Cl}. Also, a concrete of higher strength need not exhibit higher chloride resistance (i.e., lower D_{Cl}). This could be because the chloride resistance can depend on multiple physico-chemical factors such as pore structure, chloride binding capacity of cementitious material, time required for complete hydration, etc.[45]. On the other hand, compressive strength is significantly dependant on porosity[46] and may not always reflect resistance to penetration of chloride or other durability parameters of concrete.

The OPC and PFA mixes with lowest and highest D_{Cl} were selected from Table 4. Details on the concrete mixes and salient properties of the concretes considered are presented in Table 5. A typical PTC bridge girder was chosen for the study (see Figure 8(a) for geometric details). The girder has 30 strands of 15.2 mm diameter, arranged in 5 layers. The clear cover depth (d) from the soffit of the girder is 42 mm. The Cl_i and Cl_s were assumed to be 0 and 0.6% bwoc, respectively, and the rate of chloride build-up was assumed to be 0.04% bwoc. Maturity or aging coefficient (m) for the concretes were assumed based on Pillai *et al.*[25], to calculate the time-dependent D_{Cl}. The Cl_{th} values determined in this study were used for the estimation of service life using SL-Chlor, an in-house service life estimation tool developed for estimating probabilistic time to initiation of corrosion[34]. For probabilistic estimation of service life, 1000 random realizations of d, D_{Cl} and Cl_{th} (statistical distributions are provided in Table 5) were obtained. Then, $Cl(x, t)$ was determined for each year using Eq. (2) and compared with Cl_{th}. The probability of corrosion initiation was determined based on the number of instances of $Cl(d, t) > Cl_{th}$ and the cumulative distribution function (CDF) was generated. The comparison of the probability of initiation of corrosion in the PTC systems considered is shown in Figure 8(b).

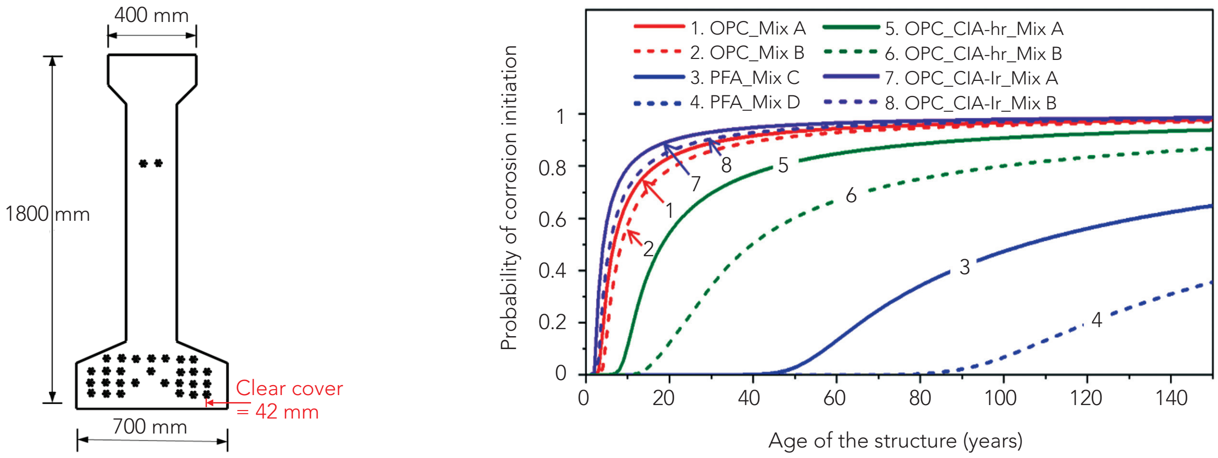
The average (i.e., $P_0 = 0.5$) service life of each system can be found from the CDFs presented in Figure 8 (b). It can be observed that all the PTC systems with OPC exhibited initiation of corrosion within 100 years. OPC systems with Mix B (with lower D_{Cl}) performed better in all the cases with OPC (Cases 1, 2, 5, 6, 7, and 8). OPC_CIA-lr exhibited the least performance followed by OPC, OPC_CIA_hr and PFA. Even the PFA concrete with high D_{Cl} (Case 3) was found to be able to provide an average service life of ≈110 years. Suitable modifications of the concrete may help in attaining the target service life for a given Cl_{th}. It should also be noted that not all commercial inhibitors have significant favourable influence on corrosion initiation.

6.3 A way forward to specify the concrete mixes – "Mx-Dy" concrete

There is a myth that 'the higher the strength, the more will be the durability'. However, it is reported that the compressive strength (f_c) has no correlation with performance indicators such as oxygen permeability index[23]. Hence, it is strongly recommended to include a durability performance parameter in the concrete specification, i.e., specify Mx-Dy concrete instead of "Mx" concrete, where x is the characteristic compressive strength at 28 days (say, M20, M30, etc.). Here, 'D' stands

Table 5: Mix design and properties of various concretes and the random variables used for case study on service life estimation[26,48]

MIX ID	A	B	C	D
Binder type	OPC	OPC	OPC+PFA	OPC+PFA
Binder content (kg/m^3)	310	340	360	380
Water content (kg/m^3)	155	187	162	133
Water-binder ratio	0.5	0.55	0.45	0.35
Fine aggregate content (kg/m^3)	743	662	723	699
Coarse aggregate (10 mm down) content (kg/m^3)	477	512	491	475
Coarse aggregate (20 mm down) content (kg/m^3)	715	768	737	713
Superplasticiser type and dosage (solid content; kg/m^3)	SNF (0.062)	-	PCE (2.34)	PCE (2.28)
Slump (mm)	100 ± 30	100 ± 30	100 ± 20	100 ± 20
Compressive strength at 28 days (MPa)	45.4	42.9	37.6	54.6
Diffusion coefficient at 28 days ($\times 10^{-11}$ m^2/s)	~N (1.87, 0.47)	~N (1.17, 0.29)	~N (0.35, 0.13)	~N (0.19, 0.048
Cl_{th} of unstressed PS steel wire (%bwob)	~N (0.40, 0.07)	~N (0.40, 0.07)	~N (0.23, 0.04)	~N (0.23, 0.04)
D (mm)	~N (42, 4.2)	~N (42, 4.2)	~N (42, 4.2)	~N (42, 4.2)



(a) Sectional details of a typical PTC girder

(b) Effect of admixed fly ash and corrosion inhibitors

Figure 8: Probabilistic service lives of PTC girder systems with various concretes

for Durability and 'y' represents the target chloride diffusion coefficient, D_{Cl}, to achieve the desired service life given the chloride exposure conditions and specified cover depth. In case of concretes with supplementary cementitious materials, the longer the age of concrete, the better will be the estimated service life; hence, preferred testing time for durability parameters could be 56 days (instead of 28 days) – provided the concrete would not get in contact or contaminated with chlorides before the testing time. Whatever be the case, one must ensure that the steel has adequate Cover depth, concrete is Compacted adequately and, Cured adequately before it is exposed to chlorides (the "3Cs") – this is the duty of all the stakeholders (say, the clients, designers, builders, inspectors, and personnel at site). It is worth an investment to deploy a person only for ensuring adequate cover depth, compaction, and curing (the "3Cs person" at site). Also, contract documents must mention the performance specifications using measurable parameters reflecting the adequate quality of the 3Cs. Such an approach will help achieve desired corrosion-free service life for PTC structures.

6.4 Limitations and future work

The present work aimed only at making a comparative analysis on the effect of PFA and CIAs on the service life of PTC systems - to aid in the selection of materials during the early stages of SLD. Hence, the Cl_{th} of unstressed PS steel was used in the presented service life analysis. However, the steel strands in PTC structures are prestressed and experience an in-service stress of 0.76 f_{pu}[21]. Therefore, for a realistic estimation of the probabilistic service life of any specific case (not within the scope of this paper), the Cl_{th} of prestressed steel should be used.

7. CONCLUSIONS

This paper shows that the chloride threshold (Cl_{th}) of unstressed prestressing steel is strongly influenced by the cementitious system. Although fly ash based systems had a lower Cl_{th} than OPC systems, PTC girders with fly ash can exhibit longer corrosion-free life than OPC systems - due to the synergistic effects of lower chloride diffusion coefficient of concrete (D_{Cl}) and lower $Cl_{th,}$ in the case of fly ash based systems. The convention of evaluating corrosion inhibiting admixtures (CIAs) based on their lower corrosion rate is inappropriate for PTC systems, because of the strong recommendation by *fib* Bulletin 34[16] to consider the limit state of depassivation for the end-of-life calculations. Hence, it is recommended that the selection of CIA should be primarily based on the synergistic effect of D_{Cl} and Cl_{th} on corrosion initiation time and not only corrosion rate and Cl_{th}. Also, to achieve desired corrosion-free service life, the paper strongly recommends to specify concretes as "Mx-Dy" concrete, where x and y represents target compressive strength and target D_{Cl}, respectively.

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