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Effect of Phosphate-based inhibitor on prestressing tendons corrosion in simulated concrete pore solution contaminated by chloride ions

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HIGHLIGHTS

- Decrease of $[Cl^-]/[OH^-]$ ratio from 0.6 to 0.4 with 80% UTS and in the absence of TSP.
- TSP enhances the critical $[Cl^-]/[OH^-]$ ratio from 0.4 to 5 under 80% UTS.
- TSP inhibitor seems to act by an anodic protection mechanism.
- AE helps to evaluate the period of time preceding the start of the material damage.

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ABSTRACT

Corrosion of prestressed concrete tendons is a huge problem that must be addressed since it can cause serious damages. This corrosion involves the synergetic effect of applied stress and aggressive environment which accelerate the material damage. The purpose of this research is to evaluate the efficiency of phosphate-based inhibitor $Na_3PO_4{\cdot}12H_2O$ against prestressed steel corrosion in chloride contaminated concrete pore solution under stress conditions. Emphasis is placed on the effect of this inhibitor on the critical $[Cl^-]/[OH^-]$ ratio for prestressing tendons corrosion initiation. The study was carried out using electrochemical techniques and Acoustic Emission (AE). Then samples surfaces were observed by Optical Microscope (MO) and analyzed by Energy Dispersive X-ray Spectroscopy (EDX). The obtained results indicate on one hand that the mechanical stress decreases the value of the critical $[Cl^-]/[OH^-]$ ratio. On the other hand the incorporation of trisodium phosphate inhibitor (TSP) enhances the critical $[Cl^-]/[OH^-]$ ratio and increases both of E_{pit} and E_{cor} values for a given ratio which suggests an anodic protection mechanism of the inhibitor. Acoustic emission evolution recorded along with the anodic polarization revealed a longer period of time for inducing the damage of the specimen when inhibitor is added. EDX analysis showed that phosphate ions are likely to form compounds that block anodic sites which help to delay prestressed steel corrosion initiation.

1. Introduction

Prestressed concrete technology has been developed in order to obtain structures with higher mechanical performance compared to conventional concrete. The method consists on tensioning high strength steel cables either before the concrete is placed (pre-tensioning) or against hardened concrete (post-tensioning) by the means of anchorage system. As a result a permanent compressive stress is applied to the material which increases its tensile strength [1]. Despite the effectiveness of this technology which is more and more adopted in the construction field typically for bridges [2,3], nuclear power plants, storage tanks, etc, corrosion is more of concern than in conventional reinforced concrete structures as prestressed elements are under high mechanical stress. Under normal conditions, steel rebars embedded in sound concrete are protected against corrosion thanks to the high pH of concrete pore solution which helps the development of a passive layer [4]. However, the stability of this latter can be compromised by two major factors: chloride ingress [5–7] and concrete carbonation [8–10]. In the case of chloride-induced corrosion, a critical chloride threshold related to steel depassivation onset is defined usually as $[Cl^-]/[OH^-]$ molar ratio or $\%Cl^-$ by weight of cement. Although numerous papers were published on this topic [11–17], it still arises controversy since many parameters should be taken into account in the assessment of chloride threshold value such as the

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experimental procedure used on that purpose [11,12], concrete mix proportions, moisture content in the concrete, blended materials, pH of the pore solution [17] and so on. In order to limit concrete reinforcement corrosion, different procedures have been developed, for instance, cathodic protection, surface treatment for steel or concrete cover, realkanization and use of corrosion inhibitors. The last mentioned method has been proved to be a good alternative since corrosion inhibitors can be easily applied either preventively (addition to concrete mixing water, steel pretreatment) or restoratively (application on the surface of hardened concrete). It was reported in the literature [18–21] that corrosion inhibitors may be classified according to their chemical composition, protection mechanism and their application procedure. Several corrosion inhibitors have been successfully used to inhibit the corrosion of steel in concrete such as nitrites, phosphates, aminoalcohols, chromates, tungstates and molybdates [22–26] but phosphates remain among the most advantageous candidates. In addition to their low cost and non toxicity, phosphates are environmental-friendly. They can already exist in solid wastes generated from beneficial operations of phosphate rocks and which can be used as filler in the cement to reduce carbon emission associated to clinker production [27]. The use of phosphate-based inhibitors has been widely studied during the two last decades in both simulating pore solution [28–37] and mortar or hardened concrete [31,32,38–41], however there is still lack of consensus about their inhibition mechanism, whether it is anodic, cathodic or mixed.

Several researchers dealt with corrosion in prestressed concrete [42–45], but as far as we know very few papers were interested in prestressing tendons corrosion inhibition [46]. Therefore we decided to test the effect of trisodium phosphate inhibitor on prestressing tendons corrosion in saturated calcium hydroxide solution contaminated with various chloride contents. The study was carried out by means of electrochemical techniques and AE which can prove to be a powerful Non Destructive Technique (NDT) for concrete structures health monitoring [47].

2. Material and experimental conditions

2.1. Material description

This study was carried out on 30 cm length ribbed steel wires of 4 mm in diameter. Chemical composition and mechanical properties of the prestressing tendons are presented in Tables 1 and 2 respectively. The material used is a hyper-eutectoid steel with fine pearlitic and fully oriented microstructure as shown in Fig. 1. Samples were polished with emery papers of grades between 80 and 4000 and then rinsed with absolute ethanol.

2.2. Testing solutions

The tests were conducted in saturated calcium hydroxide solutions (0.2% $Ca(OH)_2$) with and without 5% of Trisodium phosphate $Na_3PO_4{\cdot}12H_2O$ labeled as TSP and used as a corrosion inhibitor [28]. Chloride ions were added to these solutions in the form of NaCl up to ratios $R = [Cl^-]/[OH^-]$ varying between 0.2 and 15. R is defined as the ratio of chloride and hydroxyl ions molar concentrations. The pH value was equal to 12.7 ± 0.1. All experiments were conducted at room temperature without agitation.

Table 2
Prestressing tendons mechanical properties.

Ultimate tensile strength (UTS) (MPa)	2014
Yield strength at 0.1% (MPa)	1859
Elongation (%)	5
Striction (%)	52
Cross-section (mm^2)	12.66

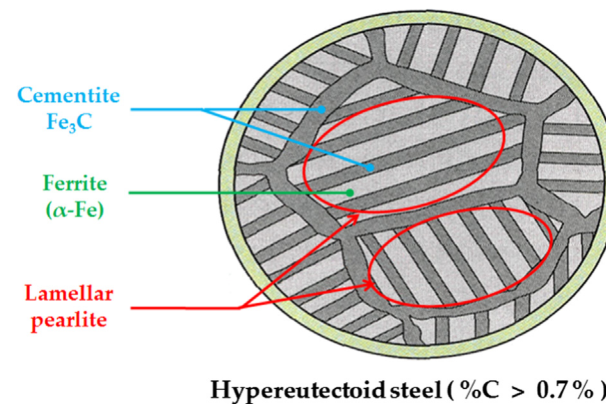

Fig. 1. Prestressing tendons microstructure.

2.3. Experimental set up

A potentiostat/potentiostat was employed for electrochemical measurements. The working electrode was the steel wire with only about 5 cm^2 area exposed. A saturated sulfate electrode Hg/Hg_2SO_4 (SSE) and a platinum plate were used as reference and counter electrodes, respectively.

The experimental device used to apply a constant stress on the prestressing tendons corresponding to 80% of the Ultimate Tensile Strength (UTS) is illustrated in Fig. 2. The electrochemical cell consisted of a cylindrical plexiglas tube of 6 cm diameter.

2.4. Experimental methods

2.4.1. Electrochemical measurements

The specimens were first exposed to the electrolytes at open circuit until stabilization of the open circuit potential (OCP) values then cyclic polarization (CP) curves were performed at a constant scan rate of 0.42 mV/s. The potential sweep starts from cathodic domain and continues in the anodic direction until the current density reaches a value of 1 mA/cm^2. The scan direction is then reversed and the final potential should be less than the corrosion potential E_{corr} value. For comparative purposes, OCP and CP tests were also carried out on non tensioned steel specimens. Electrochemical impedance spectra were recorded at OCP after 2 h immersion in the frequency range 100 kHz–10 mHz with an AC disturbance signal amplitude of 10 mV and 10 points collected

Table 1
Chemical composition of prestressing tendons.

Elements	C	Si	Mn	P	S	Cr
Wt.%	0.79–0.84	0.15–0.30	0.60–0.80	≤0.020	≤0.025	0.12–0.27
Cu	Ni	Mo	Al	N	V	Fe
≤0.15	≤0.10	≤0.020	0.005	≤0.007	≤0.06	balance