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Performance Evaluation of Corroded Post-Tensioned Tendons under Structural Loading

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Abstract: Prestressed concrete, particularly post-tensioned systems, is widely used in modern infrastructure due to its superior load-carrying capacity, crack control, and material efficiency. However, the long-term durability of such systems is significantly affected by corrosion of steel tendons, which remain hidden within ducts and are difficult to inspect. This study investigates the influence of corrosion on the mechanical and structural performance of post-tensioned tendons. The research focuses on understanding corrosion mechanisms, including chloride-induced corrosion, carbonation, and stress corrosion cracking, along with key influencing factors such as grouting quality, environmental exposure, and material properties. The effects of corrosion on tendon performance are evaluated in terms of loss of cross-sectional area, reduction in prestressing force, deterioration of bond strength, and decreased ductility and fatigue resistance. A comprehensive methodology involving literature review, analytical assessment, and proposed experimental investigation is adopted to establish relationships between corrosion levels and performance degradation. The study highlights that corrosion not only reduces load-carrying capacity but also increases the risk of brittle failure, posing serious safety concerns for aging infrastructure. The findings emphasize the need for improved design practices, effective corrosion protection systems, and regular monitoring strategies. The outcomes of this research provide a basis for predicting residual life, planning maintenance, and enhancing the durability and reliability of post-tensioned concrete structures.
Keywords— Prestressed concrete; Post-Tensioned Tendons; Corrosion Mechanisms; Structural Durability; Prestressing Force Loss

I. INTRODUCTION

Prestressed concrete has become a fundamental material in modern structural engineering due to its ability to effectively overcome the inherent limitation of concrete—its low tensile strength. The primary objective of prestressing is to introduce compressive stresses in regions that are otherwise subjected to tensile forces during service, thereby minimizing cracking and enhancing durability and load-carrying capacity. This is achieved by using high-strength steel tendons, which impart compressive forces to the concrete and enable improved structural performance.

In post-tensioned concrete systems, high-strength steel wires, strands, or bars are placed within ducts prior to casting. After the concrete attains sufficient strength, these tendons are tensioned, inducing compressive stresses within the member. The ducts are subsequently grouted with cement mortar to ensure corrosion protection and to maintain long-term structural integrity through effective bond development. Despite these advantages, the durability of prestressed concrete structures is highly dependent on material quality, workmanship, and environmental exposure conditions.

Over the past few decades, several cases of premature failure in prestressed concrete structures—particularly in countries like Germany—have been reported, primarily attributed to stress corrosion cracking (SCC) of prestressing steel. These failures are often linked to inadequate protection, poor construction practices, mechanical damage during handling, or the use of unsuitable materials. Stress corrosion cracking, especially hydrogen-induced SCC (H-SCC), is a critical deterioration mechanism that occurs when susceptible steel is exposed to tensile stress in a corrosive environment.

The occurrence of H-SCC requires three essential conditions: a sensitive material, sustained tensile stress, and a corrosive environment capable of generating atomic hydrogen. During corrosion, hydrogen atoms may be absorbed into the steel matrix, leading to the formation of microcracks, particularly along grain boundaries. These cracks can propagate under stress and ultimately result in brittle fracture of the prestressing steel.

Although concrete generally provides an alkaline environment that protects embedded steel, localized conditions such as carbonation, chloride ingress, and moisture exposure can lead to depassivation and pitting corrosion.

These localized corrosion sites create favorable conditions for hydrogen generation and accumulation, thereby increasing the risk of pitting-induced stress corrosion cracking. Consequently, understanding the interaction between material properties, environmental factors, and construction practices is essential to prevent such failures and to ensure the long-term performance of prestressed concrete structures.

Table 2: *Survey about produced prestressing steel*

type	shape, surface	diameter	anchorage system	strength class European Standard	production (world wide) tons/year
cold deformed •wire	round -smooth	4-12,2 mm	wedge or button heads	1570-1860[1)] (N/mm^2)	1.000.000 (world wide)
	round-profiled	5-5,5 mm			
•strand	round-smooth (7 wires)	9,3-15,3 mm		1700-2060[1)] (N/mm^2)	
hot rolled •bar	round-smooth	26-36 mm	thread (ends)	1030-1230 (N/mm^2)	50.000 (Germany, UK)
	round-ribbes	26,5-36 mm	thread (full length)		
quenched and tempered •wire	round-smooth	6-14 mm	wedge	1570 (N/mm^2)	5.000 (Germany, Japan)
	round-ribbed	5-14 mm			
	oval-ribbed	40-120 mm^2			

[1)]in Germany max.1770 N/mm^2

Table 3: *Advantages and application of prestressing steel*

type	especial advantage	application
cold deformed •wire	• economically to produce • high strength • low coil diameter, high coil weight (strand) • flexible tension members (strand)	for all types of prestressing and all types of elements
•strand	• easy to install (strand) • good bond behaviour (strand)	
hot rolled •bar	• tension members with high load • simple to anchor • easy handling • effective bond of ribs	transverse prestressing, earth anchors
quenched and tempered •wire	• very good bond behaviour	prefabricated elements, sleeper (railway)

Fig. 1 (a) Heating and (b) loading schemes of the stressed condition.

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II. PRESTRESSING STEEL

Prestressing wire is produced for use in prestressing applications, such as prestressed pipe, wire-wound concrete tanks, luminaire and signal poles, and rail ties. Prestressing wire is also manufactured for seven-wire prestressing strand. Typical chemical compositions and manufacturing techniques for the production of wire are described in this section. Details relating to the use of wire in the production of prestressing strand are discussed in Section 2.2. The high tensile strength obtained in cold-drawn, high-carbon steel wire is the result of three strengthening characteristics:

- Chemical content;
- Thermal treatment; and
- Deformation strengthening (cold working).

1) Chemical composition–

Current ASTM standards applicable to the several types of high-strength steel prestressing wire specify steel compositions reflective of ingot cast steel. Before the late 1980s, open-hearth and electric-furnace ingot-cast steel had been the primary source material for high-strength wire rod. The composition of high-carbon, ingot- cast steels for those products has been based on high carbon and manganese with limitations on deleterious elements, such as sulfur and phosphorus. Ingot-cast steel has been virtually replaced in the United States by continuous-cast steel for high-strength steel wire and strand products. The traditional high carbon and manganese composition of ingot-cast steel rod has been supplemented with micro alloying additions of grain refining and strengthening elements to produce a steel composition more suitable to the requirements of the continuous casting process. In addition to high carbon and manganese, continuous cast steel contains relatively small amounts, generally less than0.20%, of alloying elements, such as chromium, vanadium, or both, to achieve the minimum required mechanical properties in the finished rod. Current ASTM standards do not specify composition ranges or limits for either the micro alloying elements or minor and tramp elements, such as nitrogen These elements, however, are generally included in contemporary rod purchase specifications and are analysed for control by the steel producers.

2) Thermal treatment –

As-rolled rod does not have the proper microstructure or mechanical properties required for drawing into high-tensile- strength wire. Thermal treatment of the rod is required to produce a very fine lamellar pearlitic microstructure with the proper tensile strength and ductility for wire drawing. Two different thermal treatments have been used. Before the 1980s, the most widely used thermal treatment for rod was lead patenting. Lead patenting, generally performed by the wire manufacturer at the wire mill, requires uncoiling multiple coils of rod and simultaneously pulling the parallel strands through a furnace to heat the rods above the transformation temperature. Immediately upon exiting the furnace, the heated rods are quenched in a molten lead bath to isothermally transform the microstructure into fine lamellar pearlite. The rods are subsequently cooled and recoiled before cleaning and wire drawing. With the emergence of continuous casting of high-carbon steels and the high relative cost and environmental concerns associated with molten-lead baths for patenting, thermal treatment of rod has become incorporated in the finishing process at the rod mill. This thermal treatment practice, known as the Stanmore Process, has all but replaced lead patenting in the manufacturing of high-carbon, high- strength prestressing wire. In the Stelmore Process, hot-rolled rod emerging from the last stand on the mill is rapidly cooled with water to approximately 1500 F (815 C) and laid in a continuous spiral on a moving chain or a roller bed. The spiral of rod immediately passes over large fans that blow air against the exposed hot strands. The rapid cooling of the rod by the air transforms the steel into the fine pearlite microstructure required for drawing high-tensile-strength wire. The tensile strength of the finished, thermally treated rod, typically 160 ksi (1100 MPa) or higher.

III. EXPERIMENTAL RESULTS

Free potential versus time of steel wire during the tests is reported in Figure 2. After stabilization, and depending on crevice corrosion initiation time, free potential values ranged between –540 and – 470 mV (vs SCE). Such values lied well above the limit indicated by the equation proposed by Andrade et al. (2001) for critical chloride content for pitting initiation (Figure 3)

$E = 310\times \log[Cl^- / OH^-] - 15\ p$.

No corrosion attacks were in effect evidenced on free steel surface after solution removal. Immersion test were ended after about 54 days (1280 h) even if no complete steel wire failures were observed. After removal of Teflon ring strong crevice attack was observed on some samples. Before samples observation corrosion products were removed by means of Clarke's solution (ASTM 1981).

A typical crevice attack was shown in Figure 4. Where crevice attack was particular intense complete disruption of steel occurred, corrosion being strongly influenced by steel drawing direction. No evidence of other type of corrosion damages wereobserved on such areas. Where crevice attack was less pronounced transversal cracks on steel surface were observed.

Crackswere comparable for extension, and in some case for penetration depth, to those one observed on sample tested in solution A (thiocyanate solution) as shown in Figure 6.

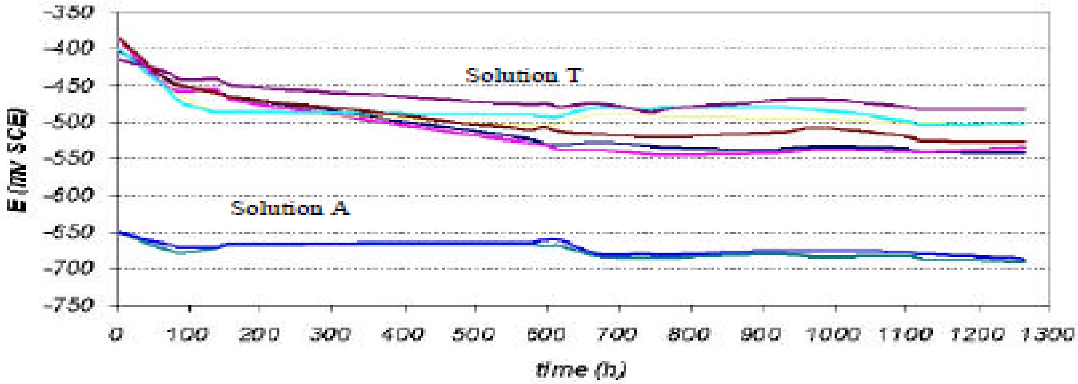

Figure 2. Free corrosion potential of steel wires in solution T and A.

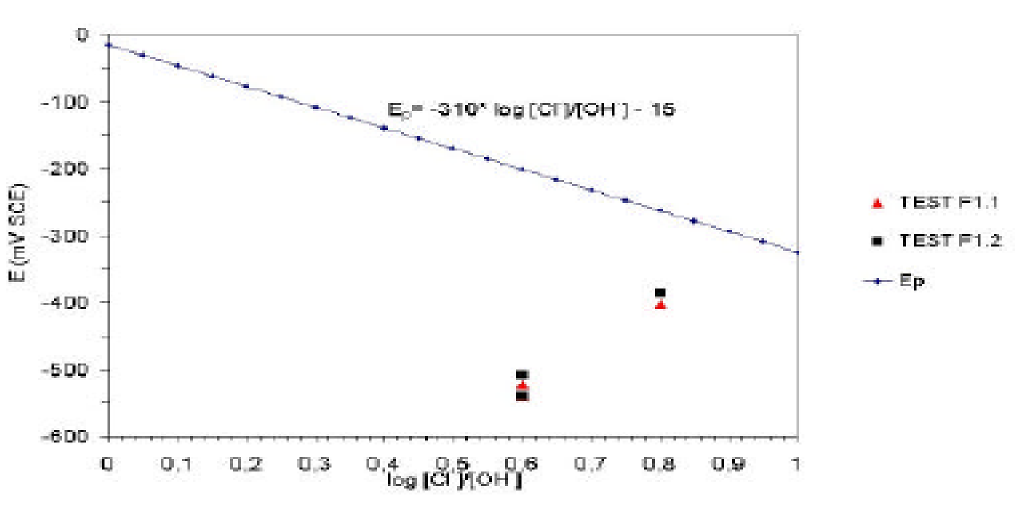

Figure 3. Free corrosion potential of steel wires in solution T vs log[Cl⁻]/[OH⁻]

No corrosion attack was observed on free steel surface of wire strand ("bundle" condition) as removed from solution T, unbinding steel wires revealed crevice corrosion development on contact surface between inner wires, corrosion attack being concentrated on an helical line following wires disposition (Figure 7). Strands were however not subjected to bendingcondition due to difficulties encountered in applying a sufficient stress to the samples without causing wire opening, so it wasnot possible to evaluate the influence of stress on evolution of corrosion attack for such type of samples.

A. DISCUSSION

Failure of prestressing steel is generally induced by corrosion. When corrosion attack is generalized (it occurs for examples in carbonated concrete or when steel is exposed directly to the atmosphere) failure occurs when cross section reduction, due to steel consumption, leads to an increase of stress in steel that overpass its UTS. It is well known however that prestressing steel is susceptible to stress corrosion cracking (SCC) (ACI Committee 222 2001; Alonso et al. 1993) and to hydrogen embrittlement (HE) (Mietz 1998). In some case brittle fracture is induced by localized corrosion attack, such as pitting (acidification at the pit tip allows hydrogen reduction and, as a consequence, hydrogen embrittlement of the steel).

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Cracks formation was in fact observed in some case at the bottom of pits (Nurnberger 1992). Relatively few failures in the literature are attributed to brittle mechanism such as SCC and HE. One possible reason is that the prestressing steels normally used in prestressed concrete construction resist this type of failure quite well if we except special sensitive prestressing steel used during the '50s and the '60s in Germany (Nurnberger 2000). A number of problems have occurred on prestressed concrete structures in recent years that are not reported in literature. This probably because the failures have generated litigation with closure of trial proceedings or nondisclosure agreements between litigant. Another possible reason is that failures may have occurred in conjunction with pitting corrosion. In this case, the investigators may not realize that the failure are due to brittle HE because of the heavy pitting damage that may be present (ACI Committee 222 2001). Brittle behaviour of steel wires extracted from heavily corroded prestressing cable taken from a prestressed concrete bridge was observed by Vehovar et al. (1998). It was supposed that low pH carbonated grouting mixture (pH ranging from 11.3 to 11.6) and the high amount of chloride present (1.1 wt % of concrete) allowed intense pitting corrosion to occur. Cherry and Price conducted tests with two different strain rate on smooth, cold drown, stress-relieved prestressing wire (1800 MPa UTS) to determine if sodium-chloride solutions of varying pH and anodic polarization would cause SCC (Cherry and 9DBMC-2002 Paper 026 Page 7 Price 1980). Wire fractured on both tests. Cherry and Price assumed that since failure of the wires were by yield at the point where the cross-section has been reduced by pitting, hydrogen embrittlement does not lead to a synergistic interaction between stress and corrosion so that failure may be ascribed simply to pitting or crevice corrosion caused by the presences of chlorides. Results reported in this work on the other hand, even if not conclusive, confirmed the evolution of hydrogen induced cracks (HICs) on steel surface in the acid environment of crevice, their growth was presumably strongly influenced by the stress condition which concentrate maximum stress on a limited section of the wire. It has to be stressed however that the major damage of steel wire was caused by the strong acid attack which interested more than the half section of the wire and that, for this type of prestressing steel, could be considered the main cause of the incipient wire failure. Further work on different type of prestressing steel (considering more hydrogen sensitive steel) was therefore planned for the future.

B. CONCLUSIONS

The results shown in the paper suggested that crevice condition, that can easily occur in restressing steel in concrete construction due to execution faults or construction errors, may lead to severe corrosion attack. Crevice can also occur in chloride contaminated concrete on inner wire surface of wire strands.

Hydrogen induced cracks can develop in such condition on steel wire. On the basis of the results here reported it was however still difficult to evaluate the influence of such cracks on the failure of restressing steel.

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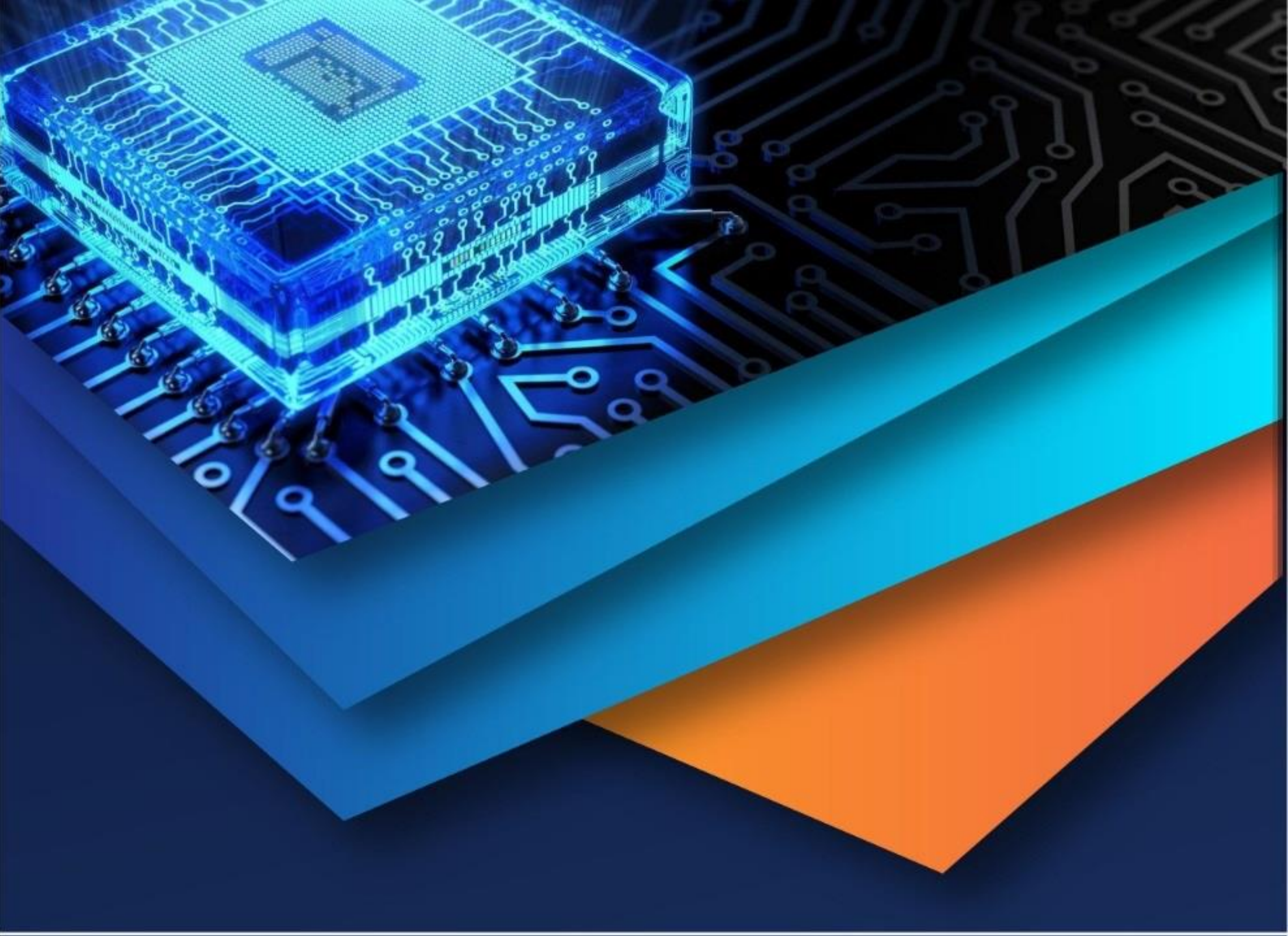

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