# Report on Corrosion of Prestressing Steels

Reported by ACI Committee 222

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*This report covers various types of prestressing steel, including some discussion on metallurgical differences, and supplements information presented in ACI 222R to include topics specifically related to prestressing steels. Deterioration mechanisms are discussed, including hydrogen embrittlement and stress-corrosion cracking. Methods to protect prestressing steel against corrosion in new construction are presented, along with a discussion of field performance of prestressed concrete structures. Finally, field evaluation and remediation techniques are presented. Appendixes present detailed information on stress-corrosion cracking and hydrogen embrittlement issues in prestressed concrete and mitigation techniques.*

**Keywords:** anchorage; bonded; corrosion; duct; durability; grout; hydrogen embrittlement; post-tensioned; prestressed; tendon; strand; stress-corrosion cracking; unbonded.

### CONTENTS





ACI 222.2R-14 supercedes ACI 222.2R-01 and was adopted and published October 2014.

## CHAPTER 1—INTRODUCTION

### 1.1—Background

Several attempts were made to prestress concrete in the 1800s, but modern development of prestressed concrete began in 1928 and is credited to E. Freyssinet of France (Lin and Burns 1981). Freyssinet understood the importance of prestressing using high-strength steel to avoid prestressing losses that significantly reduce the applied prestressing force. Use of prestressed concrete began in the United States with circular-wrapped prestressed tanks in 1941 (Schupack 1964). The first prestressed segmental concrete bridge in the United States was constructed in Madison County, TN, and opened to the public on October 28, 1950 (Bennett et al. 2002). The Walnut Lane Memorial Bridge, located in Pennsylvania, was completed in the fall of 1950 (Manning 1988). Applications of prestressing in bridge and building construction then spread rapidly and have proven to be a successful construction method. Prestressed concrete construction enhances structural efficiency, improves control of flexural cracking, and allows for structural members with reduced dimensions.

Although corrosion is not as well documented in prestressed concrete structures as in nonprestressed concrete structures, prestressed concrete members have a number of advantages regarding corrosion performance over conventional nonprestressed concrete elements. In general, prestressed concrete construction follows higher-quality control practices and material standards than conventional nonprestressed construction. These practices result in improved concrete properties that limit diffusion of chloride, which is further reduced in prestressed concrete members due to absence or reduced-level cracking. Corrosion of prestressed concrete structures appears to be restricted to specific circumstances, including improper design, construction details, and construction practices. The potential for accelerated corrosion still exists in environments contaminated with chloride ions and hydrogen sulfide and it is imperative to protect prestressing steel. Corrosion of prestressing steel in bridges and buildings may not display outward signs of corrosion. Because failure of prestressing tendons could compromise the integrity of the structure, structures subjected to corrosive conditions should be periodically inspected with specific attention focused on the condition of the prestressing system.

A number of surveys provide information concerning the potential for corrosion of prestressed structures. Burdekin and Rothwell (1981) summarized practice, specifications, and corrosion mechanisms (1981) and reported that failure to provide adequate structural details and follow proper construction practices, as well as use of low-quality materials, account for the vast majority of poor performance. Schupack reached similar conclusions in additional surveys (Schupack 1978a, 1994; Schupack and Suarez 1982). More recently, corrosion problems were discovered in grouted post-tensioned bridges (Poston et al. 2003; Hartt and Venugopalan 2002; Muszynski 2003). The problems were largely attributed to inadequate post-tensioning details and grouting practices and deficient grout materials that led to accumulation of bleedwater voids.

Because corrosion in prestressed concrete members can potentially result in fracture-critical modes of failure, more information needs to be developed, disseminated, and used. The magnitude of the corrosion problem, its projected extent, and measures that can resolve it are of vital concern to designers, contractors, and owners, and form the basis of this report.

Prestressed concrete is used in several types of construction and is described as either pretensioned or post-tensioned, depending on whether the tendons are stressed before (pre) or after (post) the concrete is placed. Pretensioned concrete refers to systems in which high-strength wires or strands are stressed in forms between bulkheads before placement of the concrete. Concrete is cast and allowed to cure to a specified strength. Because the prestressing steel is bonded with the concrete, when the steel is released from the bulkheads, the concrete is placed in compression to equilibrate the tensile forces present in the steel. Pretensioning is common practice for both standardized precast bridge girders and in precast structural building members, such as solid joists, solid and hollow-core planks, and single- and double-tee joists.

Post-tensioned concrete refers to systems in which the concrete is placed and allowed to cure to a specified strength before prestressing. Post-tensioning is applied using either bonded or unbonded tendons. Bonded post-tensioning requires that tubes or ducts with deformations be placed in the forms before concrete placement. After the concrete is placed and cured to a specified strength, bundles of strands, wires, or bars in the ducts are stressed against and anchored to the concrete. These bundles are called tendons.

In the case of bonded tendon, after tendons have been installed and stressed and concrete has been placed and reached a strength such that tendon stressing can be performed, a grout that is a mixture of portland cement, water, and admixtures is pumped into the ducts. Ducts can be metallic or nonmetallic and include uncoated or coated steel, high-density polyethylene (HDPE), and polypropylene. The grout fills spaces among the individual tendon strands, wires, or bars and between the tendon and duct. The grout provides two benefits: corrosion protection for the tendon with the highly alkaline environment provided by the grout, and bond between the concrete and the tendon. Bonded prestressing is popular in bridges, buildings, dams, tanks, and tie-backs, and may be used with both precast and cast-in-place concrete construction.

Unbonded post-tensioning commonly uses single-strand tendons. Each strand is surrounded by an individual sheath and the annular space is filled with a post-tensioning coating (grease or wax) that inhibits corrosion and reduces friction between prestressing steel and sheathing. The tendon is installed in the formwork before placement of concrete. The sheath provides a barrier between the coated strand and the concrete, and allows the strand to be stressed after concrete placement. Usually, anchorages are cast into the concrete along with the tendon. Unbonded multistrand tendons have been used extensively in nuclear pressure vessels. Multiple wires or strands are placed in a cast-in-place duct that is usually filled with heated, corrosion-inhibiting, wax-like hydrophobic grease.

Prestressing bars are widely used in bonded post-tensioning of liquid-containing tanks, in geotechnical applications such as foundation tie-downs and foundation wall tie-backs, and in segmental bridge construction.

Prestressing wire is used in the construction of prestressed concrete tanks and the manufacture of concrete pipe. In tank construction, the wire under tension is wrapped around the tank circumference. This provides a circumferential compressive prestressing force that resists the radial tensile stresses developed by filling the tank. Prestressed concrete pipe is manufactured in a similar manner where the pipe is wound with high-strength prestressing wire.

### 1.2—Scope

This report covers practices and research relating to corrosion in prestressed concrete systems, including prestressing tendons and other hardware associated with prestressing such as anchorages and ducts that also affect corrosion resistance. In general, ACI 222R covers mechanisms of corrosion of nonprestressed steel in concrete, measures for protecting embedded metal in concrete, techniques for detecting corrosion in structures, and remedial procedures. Many of the mechanisms reported in ACI 222R are valid for and apply to prestressing steels in concrete, and this report supplements ACI 222R. The metallurgy of various common prestressing steels is presented to provide necessary information to understand the mechanisms of deterioration of prestressing steels. Current and proposed techniques for evaluation of prestressed concrete structures with respect to corrosion of strands and tendons are also reviewed. A history of field performance, covering documented cases of corrosion-induced failures in prestressed concrete members, is included in this report. Finally, this document describes methods of protection and remedial techniques applicable to existing structures that exhibit corrosion. Information within this report is applicable to most forms of prestressed concrete construction, including buildings, bridges and parking structures. Prestressed tanks, pipes, and ground anchors are not specifically addressed.

## CHAPTER 2—DEFINITIONS

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," http://www.concrete.org/Tools/ConcreteTerminology.aspx.

## CHAPTER 3—PRESTRESSING STEELS

### 3.1—Wire

Prestressing wire contains high carbon and manganese contents and relatively small amounts of alloying elements, such as chromium, vanadium, or both, to achieve the minimum required mechanical properties in hot-rolled rod. The hot-rolled rod is rapidly cooled to impart the microstructure and mechanical properties required for drawing into high-tensile-strength wire. Cold-working results in a 60 to 85 percent reduction in cross-sectional area and is carried out by drawing the wire through a number of consecutive wire-drawing dies of decreasing diameter in a continuous operation. The final step is stress-relieving that increases wire ductility without sacrificing the increased yield strength achieved through cold-working. Details of the chemical compositions and manufacturing techniques for wire production are described in Appendix A.

### 3.2—Strand

Strand is produced from cold-drawn, high-strength wire. Before stress-relieving, the finished wire is wound into a seven-wire bundle in which six wires are helically wrapped around a single straight king wire. The strand may then be stress-relieved or, more commonly, stabilized and stress-relieved. Stabilization reduces relaxation characteristics of the strand by thermal-mechanical treatment—simultaneously stretching and heating the strand. The mechanical action of stretching compacts the individual wires in the strand, which reduces relaxation characteristics to below the specified level. For example, low-relaxation strand produced in accordance with ASTM A416/A416M limits relaxation loss to 3.5 percent in 1000 hours when loaded to 80 percent of its specified minimum ultimate tensile strength. Thermal treatment stress relieves the strand.

### 3.3—Bar

As with prestressing wire, high-strength bar is manufactured with controlled additions of carbon and manganese to iron. Threaded prestressing bars are manufactured from billet steel produced in an electric furnace in which the steel is melted, alloyed, and cast into billets for use in the bar hot-rolling process. The billets are reheated and hot-rolled into the bar configuration. The rolling process involves continuously feeding a bar through several stands that successively reduce bar diameter to the desired size. The last rolling places thread impressions into the bar. Unlike the strand-drawing operation, the bar is rolled under tension-free conditions so the threads on the bar are not distorted. Following the rolling operation, bars are cut to length and cooled. After cooling, the yield point of the bars is raised by cold stretching. Residual stresses from cooling and stretching are then removed with thermal stress relieving by heating to 700°F (370°C) in a furnace or with electrical induction heating.

## CHAPTER 4—DETERIORATION OF PRESTRESSING STEEL

As noted in Chapter 1, prestressing steel is used in both pretensioned and post-tensioned applications. Pretensioned applications involve direct contact between concrete and prestressing steel. The alkaline environment provided by chloride-free concrete protects prestressing steel from corrosion just as for reinforcing bars. The same is true of post-tensioned concrete structures with grouted tendons. Satisfactory protection depends on the concrete or grout quality, cover depth, and the degree to which good practices are followed throughout the design and construction operation.

Unbonded tendons are generally protected by a plastic sheath and anticorrosive grease filling the annular space around the strand. Tendon technology and field experience with unbonded tendons has improved over the past 15 years. ACI 423.4R covers the history of unbonded tendons, including field problems, and provides guidance on evaluating corrosion damage and repair methods. ACI 423.4R does not cover the metallurgy and deterioration mechanisms in as much detail as this report.

Pretensioned and post-tensioned systems that are properly detailed and constructed are adequately protected for the life of the structure. Prestressing corrosion occurs in poorly detailed or constructed systems, when inadequate materials are used, or in systems subjected to environments more severe than expected. Experience shows that a reduction in the cross-sectional area in nonprestressed steel reinforcement due to corrosion is generally not a primary concern. Corrosion of nonprestressed steel causes problems such as unsightly staining, spalling, and other serviceability-related issues, long before the loss of the steel cross section becomes an issue. On the contrary, loss of cross-sectional area of prestressing steel due to general or pitting corrosion is a major problem for two reasons.

1. Prestressing steel experiences a continuous applied stress level of 55 to 65 percent of its ultimate tensile strength throughout its life. This value can be temporarily higher during stressing. Loss of cross section increases net tension stress and can lead to local yielding and fracture.
2. Prestressing steel strength is normally four to five times higher than that of nonprestressed reinforcing steel and, as a result, is typically used in the form of smaller diameter wires than typical for nonprestressed reinforcement. The smaller-diameter prestressing steel wires will lose relative cross-sectional area faster than larger nonprestressed reinforcing bars undergoing the same corrosion rate. Remedial efforts for corrosion-damaged, prestressed concrete structures should consider this difference.

ACI defines corrosion as destruction of metal by chemical, electrochemical, or electrolytic reaction within its environment. The fundamental mechanisms for corrosion of prestressing steel in concrete are essentially the same as those for lower-grade reinforcing bars (Manning 1988; Perenchio et al. 1989; Whiting et. al 1993). ACI 222R provides complete details of the fundamental mechanisms of general and pitting corrosion of metals in contact with concrete.

Bonded, post-tensioned tendons are in contact with a portland cement grout. This grout is pumped into a polyethylene or galvanized steel duct embedded in the concrete. This system should give superior corrosion protection over pretensioned construction because of the additional barriers (Whiting et al. 1993). This can be true when the duct is properly and solidly filled with grout. A number of problems have been attributed to the lack of grout or improper pumping techniques (Novokshchenov 1989a, 1991; Ohta et al. 1992; The Concrete Society 2002; Woolley and Clark 1993). In addition, the performance of prestressing steel embedded in concrete may not necessarily be indicative of the behavior of bonded post-tensioned systems where ducts, grouts, and anchorage hardware can also have an impact on corrosion behavior (Perenchio et al. 1989). Most problems associated with bonded post-tensioned construction occur as a result of a grout deficiency. Further discussion of this issue is presented in Chapter 8.

In addition to general or pitting corrosion damage of reinforcing bars, prestressing strand and wire have increased susceptibility to other types of damage that are not usually of concern for lower-grade steel. Damage from environmentally assisted cracking mechanisms (that is, hydrogen embrittlement [HE] and stress-corrosion cracking [SCC]), fretting fatigue, and corrosion fatigue all can significantly affect the performance of the prestressing steel. HE is caused by the diffusion of atomic hydrogen into the metal lattice, limiting the ability for plastic deformation to occur and thus embrittling the steel. SCC can occur when local or general corrosion occurs in the presence of high tensile stresses, leading to the formation of transverse intergranular or transgranular cracking in the steel. In both cases, reduction in tensile strength and ductility can occur. Immediately before failure, there can be relatively little visible warning of these mechanisms, such as corrosion product. In addition, failures are usually brittle, with little elongation before fracture. Although relatively few failures have been attributed to one or more of these mechanisms, designers need to be