Long-Term Bridge Performance Program

SUMMARY REPORT

Literature Review of Chloride Threshold Values for Grouted Post-Tensioned Tendons

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About LTBP

This research was conducted as part of the Federal Highway Administration's Long-Term Bridge Performance (LTBP) Program. The LTBP Program is a minimum 20-year research effort to collect scientific performance field data, from a representative sample of bridges nationwide, that will help the bridge community better understand bridge deterioration and performance. The products from this program will be a collection of data-driven tools including predictive and forecasting models that will enhance the abilities of bridge owners to optimize their management of bridges.

This document describes the outcomes of a literature review conducted by the Federal Highway Administration (FHWA) to support an ongoing laboratory study on corrosion of grouted post-tensioned (PT) bridges that are affected by chloride-contaminated grouts.

Introduction

The number of prestressed concrete bridge structures utilizing high-strength 7-wire strands has increased steadily in recent years. Since the highly stressed prestressing strand is less tolerant to corrosive environments than ordinary reinforcing steel, many bridge deterioration problems associated with corrosion of prestressing strands have been reported. This trend is a particularly serious matter for PT concrete structures such as precast segmental box girder bridges. The same problem exists for stay cables of cable-stayed bridges. Although PT concrete structures are supposed to have multiple corrosion protection systems, many reported PT tendon failures occurred within 6–17 years in service. The Florida Department of Transportation (FDOT) has spent more than $55 million repairing 11 PT concrete bridges.[1] The biggest challenge for bridge owners and maintenance engineers is to ensure that these bridges are safe despite the lack of widely used, reliable inspection technologies to detect insidious strand corrosion hidden in the ducts or stay cables. A recent FHWA study determined that a magnetic-flux-based non-destructive evaluation (NDE) technology is potentially field-deployable to detect corrosion damage. However, it is still in the early stages of development and may take some years before becoming a common NDE method for routine bridge inspections. Until then, insufficient methods such as visual inspection, sounding, and destructive excavation are necessary to examine physical conditions of PT bridges.

Due to the importance of high-quality grout in PT concrete structures and cable-stayed bridges, commercially available prepackaged grout bags were introduced to the construction market along with enhanced grout installation guidelines and training certification programs. However, the recent discovery of chloride-contaminated grout in a PT concrete bridge located in Corpus Christi, TX, led to a full investigation of the risk caused by corrosion problems that may be the result of chloride-contaminated grout. The highest total chloride content found in an anchorage area of the bridge in Texas was 5.27 percent by weight of cement, and the chloride concentrations in the retained bags were as high as 0.5 percent by weight of cement.[(2)] These numbers exceed the past and current allowable limits for prestressed concrete and grout set by domestic and international regulatory committees. A prominent corrosion researcher, the late Dr. David Whiting, defined *allowable chloride limit* as the maximum amount of chloride in fresh concrete permitted by a code authority.[(3)] A *chloride threshold* is an actual chloride concentration causing corrosion initiation of a passivated (i.e., immune from corrosion) metal embedded in concrete and grout. In other words, an allowable chloride limit is "an artificial criterion set by man" as a guideline to ensure corrosion protection, whereas a chloride threshold value is the minimum concentration of chloride ions "set by nature" and is usually determined through actual experiments and experience in laboratory conditions.[(3)] The chloride threshold value is also called *critical chloride content*. In general, preset chloride limits are lower than experimentally determined chloride threshold values.

The corrosion process of metals, including the PT strands and cable wires in cementitious materials, consists of two steps: (1) corrosion initiation and (2) corrosion propagation. Corrosion initiates when the protective oxide film is compromised at and above a chloride concentration value, namely the chloride threshold value, or by carbonation (lowering pH). For chloride-induced corrosion, it is desirable to have a reliable chloride threshold value to predict when corrosion can initiate on metals embedded in a particular cementitious material, including grout. Once the corrosion begins, the corrosion propagation stage follows a kinetic process in the given condition. The rate of corrosion is influenced by many factors, including electrical resistance, temperature, dissolved oxygen, humidity, and moisture content.

Objectives

This summary report reviews historical chloride threshold values for metals in cementitious materials reported in the literature and summarizes the chloride threshold values relevant to the PT strands. Consequently, a range of reasonable chloride threshold values for PT strands based on the literature review is provided at the end of the document.

Background

Existing Codes and Standards

Internationally, there are at least 10 design codes that specify maximum allowable chloride contents in concrete and grout. Among them, domestic sources are three American Concrete Institute (ACI) codes, an American Association of State Highway and Transportation Officials (AASHTO) code, and a Post-Tensioning Institute (PTI) code. (See references 4–8.) The other five codes identified are from Canada, Japan, Europe, Hong Kong, and New Zealand. (See references 9–13.) The allowable chloride limits specified in the codes are listed in table 1. Only four codes have maximum allowable chloride limits specifically for grout. The remaining codes are for prestressed and regular reinforced concrete structures. Since both grout and prestressed concrete are cementitious materials that are in contact with highly stressed high-strength 7-wire strands and develop a protective oxide film, it is reasonable to assume that the codes and standards for prestressed concrete are applicable to grouted tendons, at least to some degree. In table 1 and throughout this summary report, chloride concentration data that were reported in units other than percent by weight of cement are converted so that the chloride data can be easily compared and plotted.

All domestic codes and the Canadian code limit either maximum allowable total (acid-soluble)

Table 1. Summary of codes/standards defining maximum allowable chloride limits in grout and prestressed concrete.					
Item No.	**Source**	**Section**	**Material**	**Limit**	**Chloride Type**
1	*AASHTO LRFD Bridge Construction Specifications*, 3rd Edition	Section 10, Prestressing, table 10.9.3.2	Grout	0.08 percent by weight of cementitious material	Total (acid-soluble) per ASTM C1152[14]
2	*Specifications for Grouting of Post-Tensioned Structures*, PTI M55.01-03	Section 3.3.4, Chloride Ion Content	Grout	0.08 percent by weight of cement	Total (acid-soluble) per ASTM C1152[14]
3	*Guide to Durable Concrete*, ACI 201.2R-08	Chapter 7, Corrosion of Metals and Other Materials Embedded in Concrete, table in section 7.2.3.4	Prestressed Concrete	0.08 percent by weight of cement	Total (acid-soluble) per ASTM C1152[14]
				0.06 percent by weight of cement	Water-soluble per ASTM C1218[15]
4	*Protection of Metals in Concrete Against Corrosion*, ACI 222R-01	Chapter 3, Protection Against Corrosion in New Construction, table 3.1	Prestressed Concrete	0.08 percent by weight of cement	Total (acid-soluble) per ASTM C1152[14]
				0.06 percent by weight of cement	Water-soluble per ASTM C1218[15]
5	*Building Code Requirements for Structural Concrete and Commentary*, ACI 318M-11	Chapter 4, Durability Requirements, table R4.3.1	Prestressed Concrete	0.06 percent by weight of cement	Water-soluble per ASTM C1218[15]
6	*Grout for prestressing tendons—Basic requirements*, European Standard EN 447	Chapter 6. Properties of Grout, section 6.1	Grout	0.10 percent by weight of cement	Sulfate ≤ 4.5 percent by weight of cement; Sulfide ≤ 0.01 percent by weight of cement.
7	*Limits on Chloride Ion Content*, Canadian Standards Association (CSA) A23.1-09	Section 4.1.1.2, Limits on chloride ion content	Prestressed Concrete	0.06 percent by weight of cementitious material	Water-soluble
8	*Chloride Content of Fresh Concrete*, New Zealand Ready Mixed Concrete Association, Inc.	Table 1, Maximum Values of Chloride Ion Content in Concrete as Placed	Prestressed Concrete	0.5 kg/m^3 chloride in concrete or 0.14 percent by weight of cement[a]	Total (acid-soluble)
9	*Guidelines for Design and Construction of Grouting for Prestressed Concrete Structures*, Japan Prestressed Concrete Engineering Association	Volume 1, section 4.2, Verification for corrosive materials existing in grout	Grout	0.3 kg/m^3 chloride in grout or 0.023 percent by weight of cement[b]	Total (acid-soluble)
10	*Code of Practice for Precast Concrete Construction*, Hong Kong Buildings Department	Chapter 2, Design, table 2.3	Prestressed Concrete	0.10 percent by weight of cement	Total (acid-soluble)

1 kg/m^3 = 1.69 lb/yd^3

[a]A converted value from 0.9 lb/yd^3 (0.5 kg/m^3) of chloride content in normal weight concrete assuming 4,100 lb/yd^3 (2,400 kg/m^3) containing 610 lb of cement/yd^3 (360 kg of cement/m^3).

[b]A converted value from 0.5 lb/yd^3 (0.3 kg/m^3) of chloride content in normal grout assuming 2,200 lb of cement/yd^3 (1,300 kg of cement/m^3).

Note: See references 4–13 for documents listed in the “Source” column.

chloride ions to 0.08 percent or maximum allowable water-soluble chloride ions to 0.06 percent by weight of cement. Water-soluble chloride ions are currently available for corrosion, and acid-soluble chloride is the total amount of chloride ions potentially available for future corrosion. Most of the published data were reported in total chloride content. European Standard EN 447 does not provide details about type of chloride (water-soluble or acid-soluble) or type of concrete placement (class 0.10 or class 0.20), but it grants the highest allowable chloride content (0.20 percent) in prestressed concrete among all the codes.[11] The Hong Kong and New Zealand codes also have high limits of 0.14 and 0.1 percent, respectively.[12,13]

In addition to these codes, some States have their own allowable chloride contents. For example, section 934 of FDOT's standard specifications requires a maximum chloride content of 0.40 lb/yd^3 (0.24 kg/m^3).[16] This is equivalent to approximately 0.067 percent by weight of cement, assuming 600 lb of cement/yd^3 of concrete (360 kg of cement/m^3 of concrete).

Corrosion of Metals in Cementitious Materials

Corrosion of metals in cementitious materials (concrete, mortar, and grout) progresses in two phases. The first phase is time to corrosion initiation, and the second phase is time to corrosion propagation. Some researchers add an intermediate phase of time to cracking, the first indication of destructive corrosion damage. Corrosion protection of metals in a cementitious material is offered by formation of a protective oxide film (passivity) on the metal surface in highly alkaline (typically pH > 13.2) environments. The corrosion initiation mechanism is a reversal of the corrosion protection mechanism: corrosion starts if the oxide film is compromised when the concentration of chloride ions at any metal/cementitious material exceeds a certain level (chloride threshold value) or when the pH of the cementitious medium drops below ~10 (carbonation). Therefore, time to corrosion initiation can be greatly extended for metals having substantially high chloride threshold values. A good example is high-grade stainless steel rebar versus conventional mild carbon steel rebar in concrete. It is widely accepted that carbon steel rebar has a chloride threshold value of about 1.2 lb/yd^3 (0.71 kg/m^3), which is equivalent to 0.03 percent by weight of concrete or 0.2 percent by weight of cement.[1] The reported chloride threshold values for different grades of stainless steel are at least 12 times higher than that of conventional rebar. In addition, the stainless steel bars exhibit a very low rate of corrosion once corrosion initiates. The rate of corrosion during corrosion propagation is also influenced by many factors, including level of chloride contamination, electrical resistance, moisture in concrete, and temperature. Once corrosion starts, reinforced concrete structures containing conventional rebar may take approximately 20 years to the first repair due to chloride-induced corrosion damage.[17] For stainless steel rebar, the inherently high chloride threshold values and low rates of corrosion can result in service life of 100 years or more in a corrosive environment.

Chloride Concentration

Chloride concentration can be classified by acid-soluble chloride and water-soluble chloride. The *acid-soluble chloride concentration* represents the total content of chloride, including free chloride ions in the cement paste pore water, chemically bound chloride ions, and physically bound chloride ions in the hydrated cementitious material. For this reason, it is also called *total chloride concentration* and includes all chloride ions that are potentially available for future corrosion in the concrete and grout matrix. The *water-soluble chloride concentration* is the amount of chloride ions dissolved in concrete, grout, or cementitious materials available for corrosion at the moment of analysis. Sometimes, it is referred to as the amount of free chloride ions. The range of water-soluble chloride ions is approximately 70–80 percent of the acid-soluble chloride ions, depending on type of cementitious material. The chloride concentrations are expressed in terms of either percent by weight of cement or percent by weight of powder sample. Glass and Buenfeld suggested that total chloride content with respect to weight of cement is best for expressing the chloride threshold value.[18]

A dimensionless ratio of $[Cl^-]/[OH^-]$ can also be used as a chloride threshold for free chloride ions in synthetic or real pore water. A wide range of values from 0.22 to 40 have been reported.[18] Because this ratio is mostly employed for sophisticated laboratory experiments and it is laborious to measure true $[Cl^-]$ and $[OH^-]$ in extracted pore water, it may be less useful for practical applications. Therefore, the $[Cl^-]/[OH^-]$ ratios reported in the literature are not analyzed in this document.

Extensive literature research revealed that there are many published chloride threshold values for reinforcing steel and prestressing steel in concrete but limited data for those in mortar and grout. This summary report compiles relevant findings of literature reviews grouped by laboratory studies and field studies and reported chloride threshold values for various metals including conventional rebar and 7-wire strand in concrete,

[1] One yd^3 (1 m^3) of normal weight concrete is assumed to be 4,000 lb (2,400 kg) containing 600 lb (360 kg) of portland cement.

mortar, and grout in chronological order. The next section includes discussion of the chloride threshold values specifically for PT strands in grout. Table 2 summarizes the selected data sets of reported chloride threshold values, testing media, testing materials, and sources of data. Figure 1 and figure 2 plot these values grouped by concrete and mortar/grout, respectively.

Literature Review Findings on Laboratory Studies

An early laboratory study on the corrosion of prestressed wire in concrete was published in 1960.[19] The objective of the study was to gain a better understanding of parameters that could influence the corrosion of prestressed wires in

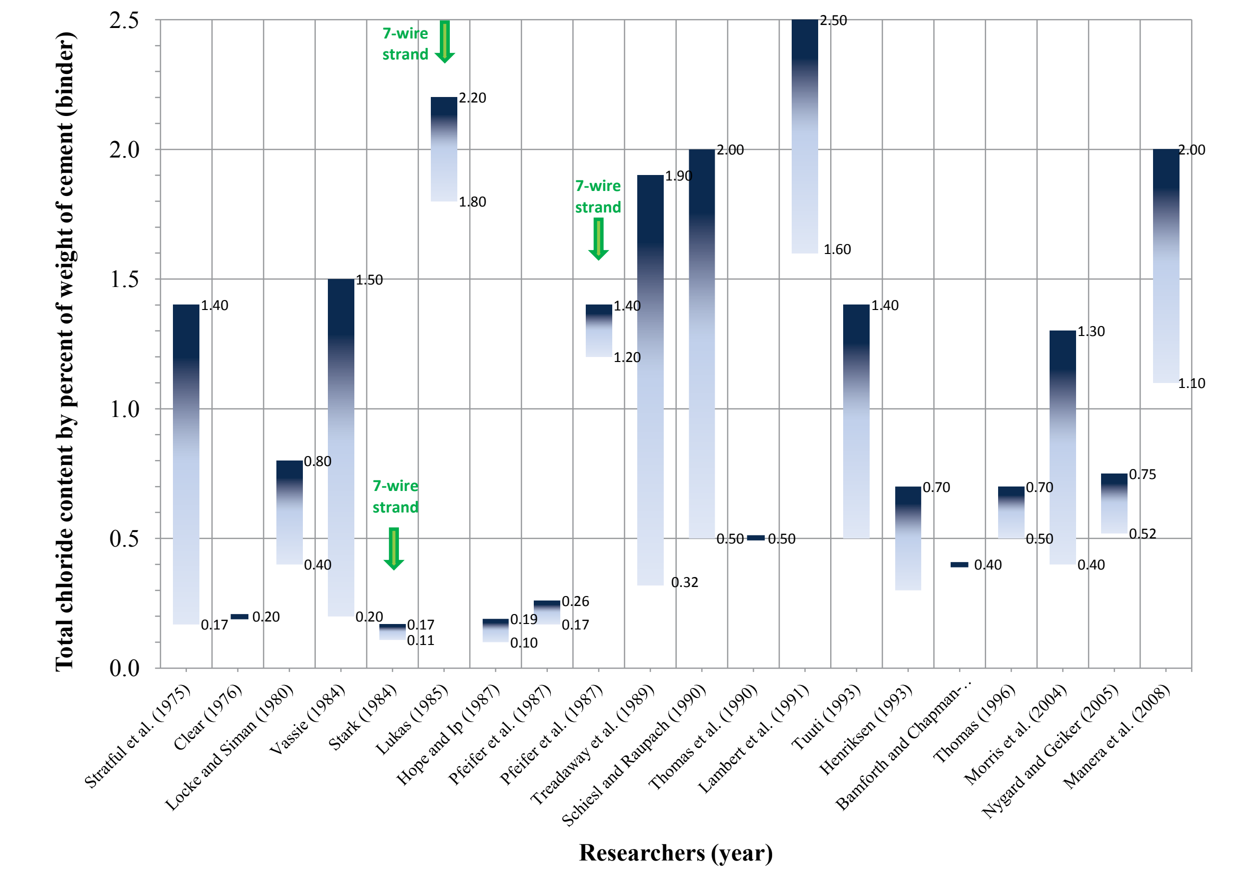
Table 2. Published total chloride threshold values relevant to this literature review.

<table>
<tr><th rowspan="2">No.</th><th rowspan="2">Researchers (Year)</th><th colspan="2">Published Total Chloride Threshold Values (Percent by Weight of Cement)</th><th rowspan="2">Testing Medium</th><th rowspan="2">Material</th><th rowspan="2">Reference No.</th></tr>
<tr><th>Max</th><th>Min</th></tr>
<tr><td>1</td><td>Elsener and Bohmi (1986)</td><td>0.5</td><td>0.25</td><td>Mortar</td><td>Sandblasted bar</td><td>23, 27</td></tr>
<tr><td>2</td><td>Hansson and Sorensen (1990)</td><td>1.6</td><td>0.4</td><td>Mortar</td><td>Unknown</td><td>18, 23</td></tr>
<tr><td>3</td><td>Alonso et al. (2000)</td><td>3.08</td><td>1.24</td><td>Mortar</td><td>Rebar and smooth bar</td><td>27</td></tr>
<tr><td>4</td><td>Zimmermann et al. (2000)</td><td>1.25</td><td>0.25</td><td>Mortar</td><td>Unknown</td><td>27</td></tr>
<tr><td>5</td><td>Trejo and Pilai (2003)</td><td>0.24</td><td>0.04</td><td>Mortar</td><td>Cleaned/degreased bar</td><td>27</td></tr>
<tr><td>6</td><td>Trejo and Monteiro (2005)</td><td>0.15</td><td>0.05</td><td>Mortar</td><td>Mill scaled bar</td><td>27</td></tr>
<tr><td>7</td><td>Sagues et al. (2005)</td><td colspan="2">0.08 by a conversion factor of 1.493 from grout weight to cement weight</td><td>Grout recharged with fresh water</td><td rowspan="5">7-wire strand</td><td>25</td></tr>
<tr><td>8</td><td>Azuma et al. (2007)</td><td>1.2</td><td>0.035</td><td>Grout</td><td>26</td></tr>
<tr><td>9</td><td>Trejo et al. (2009)</td><td>0.018</td><td>0.006</td><td>Grout</td><td>28, 29</td></tr>
<tr><td>10</td><td>Stark (1984)</td><td>0.17[a]</td><td>0.11[a]</td><td>Concrete</td><td>35</td></tr>
<tr><td>11</td><td>Pfeifer et al. (1987)</td><td>1.4</td><td>1.2</td><td>Concrete</td><td>20, 21</td></tr>
<tr><td>12</td><td>Stratful et al. (1975)</td><td>1.4</td><td>0.17</td><td>Concrete</td><td>Unknown</td><td>18, 23</td></tr>
<tr><td>13</td><td>Clear (1976)</td><td colspan="2">0.2</td><td>Concrete</td><td>Rebar</td><td>20</td></tr>
<tr><td>14</td><td>Locke and Siman (1980)</td><td>0.8</td><td>0.4</td><td>Concrete</td><td>Rebar and cleaned bar</td><td>27[b]</td></tr>
<tr><td>15</td><td>Vassie (1984)</td><td>1.5</td><td>0.2</td><td>Concrete</td><td>Unknown</td><td>18, 23</td></tr>
<tr><td>16</td><td>Lukas (1985)</td><td>2.2</td><td>1.8</td><td>Concrete</td><td>Unknown</td><td>18, 23</td></tr>
<tr><td>17</td><td>Hope and Ip (1987)</td><td>0.19</td><td>0.1</td><td>Concrete</td><td>Polished bar</td><td>27</td></tr>
<tr><td>18</td><td>Pfeifer et al. (1987)</td><td>0.26</td><td>0.17</td><td>Concrete</td><td>Rebar</td><td>20, 21</td></tr>
<tr><td>19</td><td>Treadaway et al. (1989)</td><td>1.9</td><td>0.32</td><td>Concrete</td><td>Unknown</td><td>18, 23</td></tr>
<tr><td>20</td><td>Schiesl and Raupach (1990)</td><td>2</td><td>0.5</td><td>Concrete</td><td>Unknown</td><td>18, 23</td></tr>
<tr><td>21</td><td>Thomas et al. (1990)</td><td colspan="2">0.5</td><td>Concrete</td><td>Unknown</td><td>18, 23</td></tr>
<tr><td>22</td><td>Lambert et al. (1991)</td><td>2.5</td><td>1.6</td><td>Concrete</td><td>Unknown</td><td>18, 23</td></tr>
<tr><td>23</td><td>Tuuti (1993)</td><td>1.4</td><td>0.5</td><td>Concrete</td><td>Unknown</td><td>23</td></tr>
<tr><td>24</td><td>Henriksen (1993)</td><td>0.7</td><td>0.3</td><td>Concrete</td><td>Unknown</td><td>18, 23</td></tr>
<tr><td>25</td><td>Bamforth and Chapman-Andrews (1994)</td><td colspan="2">0.4</td><td>Concrete</td><td>Unknown</td><td>18, 23</td></tr>
<tr><td>26</td><td>Thomas (1996)</td><td>0.7</td><td>0.5</td><td>Concrete</td><td>Unknown</td><td>18, 23</td></tr>
<tr><td>27</td><td>Morris et al. (2004)</td><td>1.3</td><td>0.4</td><td>Concrete</td><td>Unknown</td><td>27</td></tr>
<tr><td>28</td><td>Nygard and Geiker (2005)</td><td>0.75</td><td>0.52</td><td>Concrete</td><td>Smooth bar</td><td>27</td></tr>
<tr><td>29</td><td>Manera et al. (2008)</td><td>2</td><td>1.1</td><td>Concrete</td><td>Rebar and smooth bar</td><td>27</td></tr>
</table>

[a] Water-soluble chloride.

[b] Mean value of 0.6 reported in references 18 and 23.

Figure 1. Reported chloride threshold values for a variety of metals in concrete.

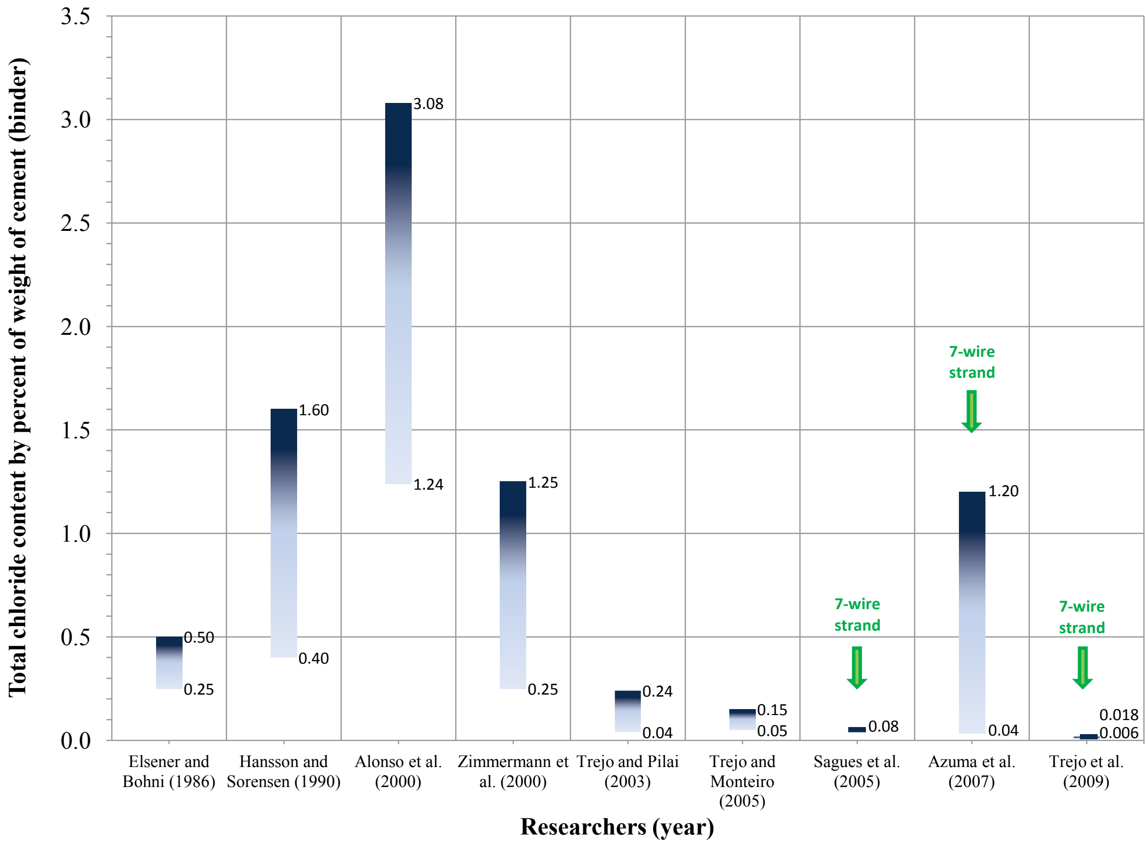


concrete. The study parameters included chloride concentration, cement type, void size, curing temperature, exposure condition, stress level, and wire type. Many of the findings are already known or irrelevant to current practice. The following summarizes several findings that may be related to PT grout:

- Corrosion took place in all wires embedded in mortar containing 4 percent by weight of calcium chloride, regardless of cement type.
- Corrosivity of sodium chloride and calcium chloride was equal.
- Fracture of the stressed wires occurred when the cross-sectional area of the wires reduced by approximately 40 percent via pitting corrosion.
- Although the stressed wires and unstressed wires experienced comparable corrosion damage in a wet exposure condition, it was inconclusive that stress would not affect the penetration rate of pitting corrosion.
- Under normal conditions, conventional concrete provided excellent protection against corrosion of prestressing wire. However, serious corrosion was possible under certain conditions for a long period of time, even when initial concentration of chloride ions was less than 1 percent in concrete.

FHWA sponsored 2 laboratory studies to investigate 11 corrosion protective systems for new prestressed concrete structures.(20,21) The 3-year study employed a total of 124 small reinforced concrete slabs and 19 full-size concrete specimens simulating columns, beams, prestressed piles, and deck panels. They were tested under two different cyclic wet and dry saltwater exposure schemes. The study determined that acid-soluble chloride threshold values for conventional rebar ranged between 0.17 and 0.26 percent by weight of cement depending on the water-to-cement ratio. The average value was 0.21 percent by weight of cement. For unstressed normal prestressing strands, the average acid-soluble chloride threshold values were 1.2 and 1.4 percent by weight of cement for as-received and ultrasonically cleaned conditions, respectively. This means that unstressed prestressing strands can withstand

Figure 2. Reported chloride threshold values for variety of metals in mortar and grout.



approximately six times as many chloride ions as conventional rebar. According to the experimental data collected from the concrete slabs containing prestressing strands with a 0.5 water-to-cement ratio and 1-inch cover, the average time to corrosion was about three times longer compared to regular rebar counterparts. Based on their findings, the authors proposed a new water-soluble chloride limit of 0.10 percent by weight of cement, instead of 0.06 percent, in prestressed concrete.(21) However, none of the ACI codes adopted the investigators' recommended limit.

The first comprehensive literature review of chloride threshold values was done during efforts to investigate the most accurate way of representing chloride threshold values.(18) Among 20 chloride threshold values reported by Glass and Buenfeld, a total of 12 values relevant to this literature review are included in table 2 and plotted in figure 1 and figure 2. None of the values was related to prestressed strands in grout. Their analysis of literature did not find evidence to support that the soluble hydroxyl ions [OH^-] associated with free chloride ions [Cl^-] in the pore water is an accurate measure of the corrosion inhibition properties of cement. Instead, they reasoned that bound chloride indicates a better corrosion risk than a [Cl^-]/[OH^-] ratio. They concluded that total chloride content relative to weight of cement is best for expressing a chloride threshold value. This measure may be viewed as the total potentially harmful chloride content rather than the total corrosion-inhibiting hydroxyl content.

Another literature review on chloride threshold contents for reinforced concrete was done by Taylor et al. in 1999.(22) The authors expressed their concern that, despite a large uncertainty involving chloride threshold values, a single threshold value was often accepted and then applied to a variety of situations. They also found researchers who believed that there is not a single threshold value but rather a range based on conditions and materials used. The authors recommended that chloride threshold content of concrete should be determined over a range of water-to-cement ratios and that these chloride contents should be distinguished by total (acid-soluble), water-soluble, and free chlorides.

Metallurgical effects on chloride threshold values for steel in concrete were investigated in conjunction with a limited literature review by Li and Sagues.[23] This study focused mainly on electrochemical behaviors of reinforcing steel in simulated pore water having different $[Cl^-]/[OH^-]$ ratios. Due to its theoretical nature, only two conclusions from this study are relevant to prestressing strands in grout, as follows:

- The chloride threshold value increased significantly with higher pH, suggesting that the inhibiting effect of $[OH^-]$ ions was stronger at higher concentrations. This means that the $[Cl^-]/[OH^-]$ ratio is not a constant.
- The large variability in the reported chloride threshold values for metals in concrete may be attributed to variability of concrete pore water pH and of chloride binding capacity.

After severe corrosion failures were observed in two major PT bridges in Florida, a laboratory study was conducted to examine corrosion susceptibility in the PT tendon anchorage area in the presence of grout voids, bleeding water, and recharging water.[24,25] The study appears to be the first major laboratory study concerning corrosion of PT tendons. Design of the study was based on several common observations related to corrosion problems found in the PT bridges, as follows:

- Corrosion was found mainly at or near the anchorages.
- The anchorage assemblies consisted of dissimilar metals (ductile cast iron anchors and forged steel wedge plates).
- Corrosion was always associated with grout voids, the presence of grout bleeding water, and soft and chalky grout in the affected areas.
- Corrosion was always, except for one instance, associated with grout containing only trace levels of chloride ions.

For this study, seven mock-up anchorage assembly specimens were fabricated using commercially available ductile cast iron anchorage assemblies, unstressed high-strength 7-wire strands, two types of grout, and simulated grout voids. The specimens were subjected to simulated water recharging events with fresh water and 0.01N sodium chloride solution. The results showed that either grout bleeding water or recharging water can be a major source of PT tendon corrosion by forming a galvanic corrosion cell. This was because the PT strands become anodic to the anchorage assembly in the presence of water. Depassivation of the strands can take place even if modest grout carbonation (pH = 8.7 ±0.5) occurs. It was observed that fresh water could initiate corrosion if the native chloride ions in the grout exceeded 500 ppm (0.08 percent by weight of cement[2]). From this, the investigators recommended lowering the allowable chloride limit. Furthermore, significant corrosion of strands was observed in the voids, especially in conditions of high relative humidity. The investigators were able to confirm that tendon failure by strand corrosion can be realized in as little as 7 years. This is consistent with the actual failure observed in the field.

Another corrosion study with chloride-contaminated grout was performed in Japan.[26] The objective of the study was to investigate whether the current allowable Japanese chloride content of 0.5 lb/yd^3 (0.3 kg/m^3) in grout was adequate for corrosion protection of stressed strands. The researchers employed five grout mixes that had a common water-to-cement ratio of 0.45 with different chloride contents of 0.035 (Japanese allowable chloride limit[3]), 0.08 (U.S. and European chloride limits), 0.30, 1.20, and 3.60 percent by weight of cement. Multiple unstressed strands and stressed strands at two levels (70 and 80 percent of the ultimate tensile strength) were covered with the grout materials. Their corrosion state was monitored by visual appearance, corrosion potential, and anodic polarization curves for up to 684 days. The study found that the prestressing level did not affect corrosion behaviors of the strands and that only strand specimens covered with 3.60 percent chloride content grout showed active corrosion by corrosion potential and anodic polarization data. At the end of the study, autopsy confirmed that corrosion was only on the strands covered with 3.60 percent chloride content grout. Therefore, the researchers concluded that grout mixes containing a chloride

[2]Portland cement weight is assumed to be 67 percent of the grout sample weight.

[3]857 kg of portland cement in 1 m^3 of grout (1,450 lb of portland cement in 1 yd^3 of grout).

concentration of 1.2 percent or less by weight of cement would not induce corrosion on the strands, regardless of the stress level.

The most thorough literature review was made by Angst et al. in 2009, with comprehensive analysis of the reported research data related to chloride threshold values.[27] The review emphasized concrete, and the majority of the information cannot be related to grout, except for the research included in table 2. The following are findings related to this literature review:

- A large scatter was observed in the reported total chloride threshold values, ranging from 0.04 to 8.34 percent by weight of cement. The scatter is caused by different experimental procedures and numerous parameters affecting chloride-induced corrosion. The highest chloride threshold value, 8.34 percent by weight of cement, is not comparable to the other reported values and appears to be an outlier.
- It has been suggested that the condition of the steel-concrete interface is the most influencing factor along with the pH of the concrete pore water and the steel potential. Ordinary rebar with rib deformation had a higher corrosion susceptibility compared to smooth bars.
- Moisture content is an influencing factor because it regulates the availability of water and oxygen at the steel/concrete interface. For either water-saturated concrete or dry concrete, higher chloride concentrations are needed to initiate corrosion. Other parameters include the following:
    - Binder type.
    - Surface condition of the steel.
    - Oxygen availability at the steel surface.
    - Water-to-cementitious binder ratio.
    - Electrical resistivity of the concrete.
    - Degree of hydration.
    - Chemical composition of the steel.
    - Temperature.
    - Source of chloride (admixed versus penetration from external environment).
    - Type of cation accompanying the chloride ion (mainly Na^{+}, Ca^{+2}).
    - Presence of corrosion-inhibiting substances.
- It is difficult to adopt a unique chloride threshold value in the real world, where there are a wide range of structures having different service conditions.
- The chloride threshold values determined in mortar and concrete tend to be higher than those measured in aqueous solutions. There is no significant difference between concrete and mortar.
- The most accurate way of determining the total chloride content in concrete powder is X-ray fluorescence spectrometry.
- The most accurate way of determining depassivation (precise chloride threshold value) is to measure corrosion potential, rate of corrosion by linear polarization resistance, and electrochemical impedance spectroscopy.

Extensive laboratory research on strand corrosion was carried out in 2009 to investigate the effect of voids in grouted PT tendons.[28,29] The objectives were to provide guidelines on corrosivity of PT stands under different environmental conditions, develop a reliability model for PT bridges suffering from strand corrosion, provide repair recommendations, and recommend inspection and repair methods of PT systems. Overall, the focus was more on structural aspects of the PT strand corrosion than on corrosion itself. Key experimental parameters included the following:

- Grout type: Class A (portland cement and water, water-to-cement ratio of 0.44) and Class C (prebagged commercial grout, water-to-cement ratio of 0.27).
- Moisture content: High (2 weeks ponding with chloride test solutions and 2 weeks drying) and low (lab air without wet and dry cycles).
- Chloride concentration: 0.0001, 0.006, 0.018, 0.18, and 1.8 percent by weight of aqueous chloride solutions.
- Void type: No voids, parallel voids, orthogonal voids, inclined voids, and bleed water voids.
- Stress level: No stress and 150 ksi (1,000 MPa) (56 percent of guaranteed ultimate tensile strength).

A total of 26 batches were made to cast corrosion specimens that were cured in the lab environment for 28 days prior to corrosion testing. All of the specimens exhibited localized corrosion at or near the grout-air interface. The specimens exposed to test solutions containing 0.018 to 1.8 percent chloride ions during the wetting cycles experienced pitting corrosion, whereas those exposed to 0.006 percent chloride ions exhibited no pitting corrosion except for severe localized corrosion at the grout-air void interface. From this finding, the researchers suggested that the chloride threshold value for the PT strands is likely between 0.006 and 0.018 percent chloride ions. The study found that condensation could lead to higher corrosion rates, but high humidity alone did not result in the same level of deterioration. When the strands were directly exposed to moisture with and without chloride ions, reduction of significant strand capacity occurred (assumed to be caused by pitting corrosion) and grout voids played a significant role. If the strands were embedded completely in grout, both unstressed and stressed strands experienced similar capacity reductions. If they were exposed in the voids, the stressed strands experienced much higher capacity losses (more corrosion damage) than the unstressed counterparts. The largest mean capacity reduction was observed when the stressed strands intersected the voids perpendicularly in grout that was exposed to 0.006 and 1.8 percent chloride ions. The researchers concluded that it is important to protect the ducts and strands from water and chlorides and also to eliminate grout voids to prevent or minimize the strand capacity reduction. According to their reliability model, a PT bridge can fail as early as 21 years after construction if the strands are subjected to high-chloride environments.

Literature Review Findings on Field Studies

There have not been many field studies of PT bridges involving grout chloride analysis. For this report, four studies were reviewed. Table 3 lists the reported chloride data in the grout samples, and figure 3 shows the variability of the data.

A large-scale field study was conducted in the early 1990s as part of the prestressed concrete technology review and condition surveys.(30) Twelve bridges exposed to a marine environment and deicing salts were surveyed in detail. They were located in Florida, Illinois, Connecticut, Rhode Island, Oregon, North Dakota, and Michigan. The field surveys utilized visual examinations, various NDE tests, and powder sampling for chloride analysis. Among the 12 bridges, 4 were PT bridges located in North Dakota, Connecticut, and Rhode Island. All of them exhibited few signs of corrosion, except for anchorage areas with varying degrees of corrosion. The Wolcott Avenue Bridge in Connecticut is a PT bridge providing useful information. Grout samples taken from the bridge were analyzed for total chloride content. As listed in table 3, the samples contained very high to very low chloride concentrations between 1.065 and 0.001 percent by weight of sample. After observing no signs of corrosion on the ducts, the investigators suspected that the chloride was added as an admixture to the fresh grout mix. A valuable finding was the discovery of virtually corrosion-free strands for 25 years of service despite being exposed to grout with as high as 1.065 percent chloride by weight of grout sample (equivalent to 1.590 percent by weight of cement[4]). The strands in the high chloride-contaminated areas "exhibited slight amounts of corrosion, but no significant loss of cross section."(30) The grout in question appeared to fill the ducts completely with little or no sign of voids. Therefore, the total chloride content of 1.590 percent by weight of cement is considered the maximum chloride threshold value in this case.

A series of field inspections and testing programs were carried out for the Sunshine Skyway Bridge in Florida after water was found inside 28 of the high-level approach columns during a routine biennial inspection in 1996.(31) A total of 146 grout samples were extracted from various locations in the columns and analyzed for acid-soluble chloride contents. A large variation of chloride concentrations was observed in the entire chloride database. The highest and lowest contents were 3.8 and 0.0026 percent by weight of grout sample, respectively. A tendon exposed to grout containing 2.26 percent total chloride by weight of cement was visually confirmed to suffer from severe corrosion. In general, the severity of the strand corrosion was related to the level of chloride concentration. The selective chloride data set having a description of observed strand corrosion is reproduced in table 3, grouped by degree of corrosion of the exposed strands. Some corrosion-free strands were observed during the investigations. The highest chloride concentration

[4]Portland cement weight is assumed to be 67 percent of the grout sample weight.

Table 3. Chloride data in the field PT grout samples.

Bridge ID	Tendon ID	Total Chloride (ppm)	Total Chloride (percent by weight of grout sample)	Total Chloride (percent by weight of cement)	Degree of Corrosion
Sunshine Skyway Bridge	131 NB-SW tendon	311	0.031	0.046	None
	132 NB-NE tendon	459	0.046	0.069	
	132 NB-NW tendon	220	0.022	0.033	
	133 NB-SE tendon	57	0.006	0.009	
	133 NB-SW tendon	985	0.099	0.147	
	133 SB-NE tendon	269	0.027	0.040	
Wolcott Avenue Bridge	Span 2-5	10,650	1.065	1.590	
	Span 2-5	6,900	0.690	1.030	
	Span 2-5	8,430	0.843	1.258	
	Span 6-6	10	0.001	0.001	
	Span 6-6	20	0.002	0.003	
Sunshine Skyway Bridge	133 NB-NE tendon	6,273	0.627	0.936	Minor
	133 NB-NW tendon	1,531	0.153	0.229	
	131 SB-NW tendon	8,435	0.844	1.259	
	131 SB-SE tendon	320	0.032	0.048	
	131 SB-SW tendon	830	0.083	0.124	
	133 SB-NW tendon	74	0.007	0.011	
	133 SB-SE tendon	1,646	0.165	0.246	
	133 SB-SW tendon	2,821	0.282	0.421	
	131 SB-NE tendon	15,164	1.516	2.263	Severe
Mid-Bay Bridge	Span 40-A tendon 2 (top)	1,000	0.010	0.012	
	Span 40-A tendon 2 (bottom)	700	0.007	0.009	
Varina-Enon Bridge	Tendon 10-E, sample 2	< 20	< 0.002	< 0.003	
	Tendon 10-E, sample 3	< 20	< 0.002	< 0.003	
	Tendon 10-E, sample 4	< 20	< 0.002	< 0.003	
	Tendon 10-E, sample 5	< 20	< 0.002	< 0.003	
	Tendon 10-E, sample 6	< 20	< 0.002	< 0.003	
	Tendon 10-E, sample 7	< 20	< 0.002	< 0.003	

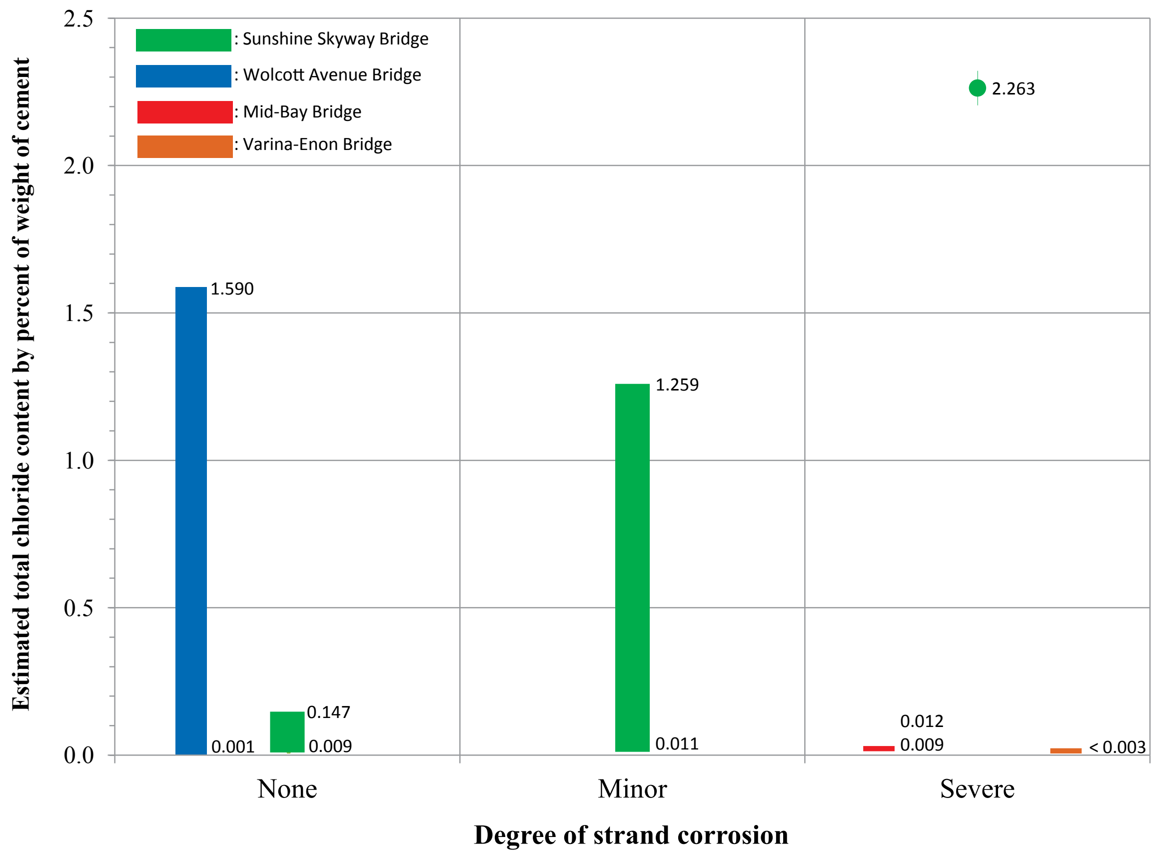
NB = Northbound; SB = Southbound; NE = Northeast; NW = Northwest; SE = Southeast; SW = Southwest.

without corrosion was 0.099 percent (985 ppm) by weight of sample collected from a primary grout of column 133 northbound. If cement weight is assumed to be 67 percent of the sample, it is equivalent to 0.147 percent by weight of cement. This can be considered the maximum chloride threshold value determined in this study.

On August 28, 2000, during a routine inspection of the Mid-Bay Bridge in Florida, significant distress was discovered in a PT tendon in span 28, including duct cracking and fracture of several strands.[32] Consequently, an onsite corrosion investigation was conducted in January 2001.[33] The investigation found that active corrosion was attributed to the following factors:

- Accumulation of excessive bleeding water during grouting.
- A negative effect of the Intraplast® N expansive admixture on corrosivity of the bleeding water.
- Hygroscopic bleeding water residuals.
- Presence of cavities and grout voids.
- Carbonated local areas due to a high water-to-cement ratio grout.

Figure 3. Comparison of total chloride concentration versus degree of strand corrosion in four bridges.



- Exposure to high relative humidity and condensation of moisture at temperatures below the dew point.

The investigators expected that once the bleeding water was reabsorbed into the grout and drying occurred, the rate of corrosion would decrease substantially. Whenever temperature drops below the dew point and during periods of high humidity, corrosion of the strands will re-initiate within grout voids or where grout has carbonated. The researchers collected 12 grout samples and conducted an analysis of total chloride. The chloride contents ranged from 0.137 to 0.259 lb/yd^3 (0.0811 to 0.153 kg/m^3) (0.007 to 0.012 percent by weight of cement[5]). Considering the ACI 222R limit of total chloride of 0.08 percent by weight of cement was equivalent to 1.7 lb/yd^3 (1.0 kg/m^3) of chloride in this study, all of the grout samples were well below the ACI allowable chloride limit.[(6)] However, four severely corroded wires were found where chloride concentrations in the grout were 0.180 and 0.259 lb/yd^3 (0.107 and 0.153 kg/m^3) (0.009 to 0.012 percent by weight of cement). From this, they concluded that the chloride threshold value becomes progressively lower with decreasing pH (carbonation). Once the grout pH drops to where passivity cannot be maintained, active corrosion can occur in the presence of oxygen and moisture regardless of chloride concentration.

Another full investigation of a PT bridge was initiated in 2007 when routine inspection of the Varina-Enon Bridge in Virginia found that one PT tendon was severed by corrosion of strands and another one was damaged.[(34)] The objectives of the investigation were to determine the causes of the tendon corrosion, evaluate the condition of the remaining 478 tendons, and develop a repair plan. The investigators claimed that the cause of the severed tendon (tendon 10-E) in span 12 southbound was caused by gypsum-based repair grout material containing excessive sulfate ions. The damage to the other tendon (tendon 1302-W) in span 19 southbound was a direct result of external corrosion initiated by

[5]The report used 2,115 lb of cement/yd^3 of grout (1,251 kg of cement/m^3 of grout) that had a unit weight of 2,550 lb (1,160 kg).

ponding water near a clogged drain hole in the box girder floor in the span. As shown in table 3, all six of the sample grout powders taken from the failed tendon had less than 0.003 percent total chloride by weight of cement. Although it is still uncertain that sulfate ions are responsible for the corrosion failure of the tendon strands, it is apparent that rapid corrosion can occur with virtually no chloride ions under certain conditions.

Findings of Chloride Threshold Values for Grouted PT Tendons

For grouted (bonded) PT tendons and cables, the grout is the last layer of corrosion protection for the highly stressed 7-wire strands and cable wires by providing a high pH environment to form a protective oxide film on the steel surface and by being a physical barrier to water and oxygen. According to the literature review, when PT tendons corrode, the common observations made are as follows:

- Accumulation of bleeding water was corrosive.
- Bleeding water residuals were hygroscopic.
- Cavities and grout voids were corrosion initiation spots.
- Carbonated local areas usually existed.
- High relative humidity and condensation of moisture facilitated active corrosion.
- Corrosion was found mainly at or near the anchorages.
- Corrosion was always associated with grout voids.
- Corrosion occurred with and without chloride ions. However, once corrosion initiated, severity of strand corrosion was closely linked to chloride concentration in the presence of moisture, water, and high humidity.

Therefore, any combination of the following seven deficiencies can trigger corrosion with the presence of moisture and oxygen: (1) voids, (2) bleeding water, (3) contamination with chloride ions, (4) low pH (carbonation), (5) sedimentation and soft grout (variable water-to-cement ratio), (6) duct cracks, and (7) water leak through anchorage zones. While some tendon corrosion cases were observed in the carbonated grouts exposed to water and oxygen, particularly in the voids, various amounts of chloride ions were found in other incidents. The effect of stress level on corrosion was inconclusive due to conflicting results.

If there are no appreciable tendon deficiencies, time to corrosion initiation of PT strands may depend on the chloride threshold values, which can be influenced by the following parameters:

- Surface condition of the steel.
- pH at the strand-grout interface. (The chloride threshold value becomes progressively lower with decreasing pH.)
- Moisture content in the grout.
- Oxygen availability at the steel surface.
- Temperature.
- Electrical resistivity of the grout.
- Degree of hydration.
- Strand-grout interface characteristics (hard grout versus soft/pasty grout).

To obtain chloride threshold values in the real world, as Angst et al. stated, individual researchers employed different experimental procedures, numerous parameters, and a wide range of structures with different service conditions.[26] As a result, there is a large variation in published chloride threshold values. This problem can be represented by each of the data plots in figure 1 through figure 3. The same plots also show that there are neither trends nor consistencies in the reported chloride threshold values. In figure 3, the total chloride contents corresponding to "no corrosion" are considered the observed chloride threshold values for two PT bridges. Recognizing the challenge in determining a chloride threshold value or a set of values based on the limited data reported in the literature, the following discussion is intended to draw conclusions with definite chloride threshold values for practical purposes.

In high-quality dense grout with high pH and in the absence of voids and water, the maximum total chloride threshold value was 1.2 percent by weight of cement in a laboratory environment and 1.590 percent by weight of cement in the Wolcott Avenue Bridge.[26,30] The former employed grouted strands without ducts and exposed the grout to the ambient air. Therefore, there were no opportunities for the strands to be exposed to high levels of moisture content. The test result suggests that the stressed strand can tolerate elevated total chloride content up to 1.2 percent by weight of cement without developing corrosion if the grout is completely dry. A similar chloride threshold value was found in the Wolcott Avenue Bridge, where the ducts were filled completely with high-quality grout with little or no sign of voids and water. In the wet, low-oxygen environment found in the Sunshine Skyway Bridge columns, the total chloride threshold value was 0.147 percent by weight of cement.[31] In unfavorable environments with defective grout, low pH, and water recharging events, the total chloride threshold values were 0.08 percent by weight of cement in a laboratory study and 0.009 percent by weight of cement in the Sunshine Skyway Bridge.[23,24,31] Another laboratory study suggested that the chloride threshold value is likely between 0.006 and 0.018 percent of total chloride ions.[28,29]

It is reasonable to assume that the total chloride threshold value for PT strands is 1.5 percent by weight of cement in the best field conditions provided by defect-free ducts and anchorage zones completely filled with high-quality grout containing no voids and moisture. In other field conditions, the value falls to between approximately 0.01 and 0.150 percent by weight of cement depending on the quality of installed grout and field exposure conditions. No matter what chloride threshold value is chosen, it is critical to remember that a chloride threshold value may suggest theoretically when corrosion of the PT strand can start. Actual chloride concentration is the main controlling factor of the active corrosion process in response to a given exposure condition. Therefore, corrosion risk will increase as chloride concentration increases under the same set of conditions.

Conclusions

Based on the findings of a literature review with emphasis on maximum allowable chloride limits and chloride threshold values pertaining to PT grout and prestressed concrete, the following conclusions are made:

- Currently, there are five domestic and five international codes that specify maximum allowable chloride contents in grout and prestressed concrete. AASHTO, PTI, European Standard EN 447, and the Japan Prestressed Concrete Engineering Association specify chloride limits in grout, and the others specify chloride limits for prestressed concrete.
- All domestic codes allow either 0.08 percent total (acid-soluble) chloride or 0.06 percent water-soluble chloride by weight of cement. In the foreign codes, the allowable total chloride content limit varies between 0.023 percent (Japan) and 0.2 percent (Europe) by weight of cement.
- For PT strands embedded in dry, high-quality grout with high pH and no voids at the strand-grout interface, the total chloride threshold value can be as high as 1.5 percent by weight of cement (or 1.0 percent by weight of grout sample).
- In other circumstances, the total chloride threshold value varies significantly between 0.01 and 0.150 percent by weight of cement (or 0.006 and 0.1 percent by weight of grout sample), depending on field exposure conditions and quality of installed grout, particularly characteristics at the strand-grout interface.
- Although the AASHTO and PTI codes allow a maximum of 0.08 percent total chloride content by weight of cement in fresh grout, a lower total chloride threshold value may be required and appears more appropriate based on literature findings presented in this report.

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