Pennsylvania Department of Transportation
Bureau of Planning and Research Project
Contract No. 355I01 / Project No. 070202

Inspection Methods & Techniques to Determine Non Visible Corrosion of Prestressing Strands in Concrete Bridge Components

Task 1 – Literature Review

September 1, 2008

By

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ATLSS REPORT NO. 08-06

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1. Literature Review of Prestressing Strand Corrosion in Concrete Systems

Included in this report is a summary of published literature relating to corrosion of prestressing strands in pre-tensioned bridge applications. The summary includes published reports from reputable organizations and refereed journal papers. The references are summarized in sections 2 through 10 of the report. Within each of these sections the title, author, and brief abstract of the publication is provided. In Section 11 a brief summary of some of the causes of corrosion in concrete (i.e. carbonation, chloride, etc) is provided. Within this section brief recommendations are made on chloride threshold values and appropriate testing methods. Section 12 summarizes the results of a PennDOT survey on Non-Composite Adjacent Prestressed Concrete Box Beam Bridges conducted in 2006. Included in this section is a brief description of failures that have occurred, the prevalence of PS adjacent box beams and the visual inspection methods used by a number of DOTs.

The goal of this report is to summarize the published literature on the subject of corrosion of prestressing steel in bridges. This report is not meant to be a guideline or recommendation on how to inspect bridge beams. Non-destructive and destructive inspection methodologies will be assessed based on forensic evaluation of recently decommissioned bridge beams from PennDOT. The outcome of this study and recommendations will be based on the findings presented in a subsequent report.

2. American Concrete Institute (ACI) Reports

The American Concrete Institute has dedicated a significant effort toward describing the causes, implications, and methods of abating corrosion of reinforcement in concrete members. Three documents have been produced by ACI committee 222 Corrosion of Metals in Concrete. These documents provide the most current and thorough state of the knowledge on this subject of corrosion of steels in concrete.

ACI 222R provides the most concise and thorough overview of corrosion of steels in concrete published to date. The report includes a discussion on the corrosion process, inspection techniques, and abatement methods. ACI 222.2 provides additional information directly related to corrosion of prestressing steels. ACI 222.3 provides an overview of techniques that can be used to mitigate corrosion. The final ACI document referenced is ACI 201. This report provides guidance on how to properly conduct a visual inspection of a concrete member.

2.1. Protection of Metals in Concrete against Corrosion (ACI 222R-01)

Author(s): ACI Committee 222

Publication: ACI 222R-01

Publication Date: 2001

Abstract: This report reflects the state of the art of corrosion of metals, and especially reinforcing steel, in concrete. Separate chapters are devoted to the mechanisms of the corrosion of metals in concrete, protective measures for new concrete construction, procedures for identifying corrosive environments and active corrosion in concrete, and remedial measures.

2.2. Corrosion of Prestressing Steels (ACI 222.2R-01)

Author(s): ACI Committee 222

Publication: ACI 222.2R-01

Publication Date: 2001

Abstract: This report reflects the current understanding of corrosion of prestressing steels in concrete. The report includes chapters that cover the various types of prestressing steel, including some discussion on metallurgical differences. 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.

2.3. Design and Construction Practices to Mitigate Corrosion of Reinforcement in Concrete Structures (ACI 222.3R-03)

Author(s): ACI Committee 222

Publication: ACI 222.3R-03

Publication Date: 2003

Abstract: Corrosion of metals in concrete is a serious problem throughout the world. In many instances, corrosion can be avoided if proper attention is given to detailing, concrete materials and mixture designs, and construction practices. This guide contains information on aspects of each of these. In addition, the guide contains recommendations for protecting in-service

structures exposed to corrosive conditions. The guide is intended for designers, materials suppliers, contractors, and all others engaged in concrete construction.

2.4. Guide for Making a Condition Survey of Concrete in Service (ACI 201.1R-92)

Authors: ACI Committee 201

Publication: ACI 201.1R-92

Publication Date: Reapproved 1997

Scope: This guide provides a system for reporting on the condition of concrete in service. It includes a checklist of the many details that may be considered in making a report, and repeats the ACI 116R standard definitions of terms associated with the durability of concrete. Its purpose is to establish a uniform system for evaluating the condition of concrete.

3. National Cooperative Highway Research Program (NCHRP) Reports

Three studies on corrosion of steel in bridge applications have been conducted under the National Cooperative Highway Research Program (NCHRP). The program is administered by the Transportation Research Board and sponsored solely by state departments of transportation. The funding for the projects comes directly from each States Planning and Research funds. On completion of the research project an official NCHRP report is produced. A literature search of the program returned three applicable studies. Two studies have been completed and one is underway. They are summarized in this chapter.

The first report NCHRP 558 provides a thorough methodology for assessing the condition of bridge elements. The report is formulated in a similar manner to ACI 222R however additional information is provided on determination of service life and actual methodologies for inspection. The recommendations are limited to conventionally reinforced members however many of the procedures can be directly applied to PS concrete beam inspection.

The second report (web document 23) provides a study of NDE methods for assessing condition of PS strands. The 1999 study found that the "current state of the art will not permit an evaluation of the embedded prestressing strand's condition as precisely and broadly as sought in the NCHRP project goals…" where the goals of the project were to identify loss of cross sectional area in strand attributable to corrosion and cracking. As a result a planned follow-on study was not pursued.

The last reference discusses ongoing work which relates directly to the issue of adjacent PS concrete box beam bridges. The goal of the work is to develop improved construction practices for the grout key used between members. In addition inspection methods are being developed. The work is still in progress however due to the direct applicability of the research the results outcomes should be monitored.

3.1. Manual on Service Life of Corrosion-Damaged Reinforced Concrete Bridge Superstructure Elements

Author(s): Ali Akbar Sohanghpurwala

Publication: NCHRP Report 558

Publication Date: 2006

Abstract: This report is a manual that provides step-by-step procedures for assessing the condition of corrosion-damaged bridge elements. It also includes procedures that can be used to estimate the expected remaining life of reinforced concrete bridge superstructure elements and to determine the effects of maintenance and repair options on their service life. This manual should be of interest to state engineers and others involved in the design, construction, and maintenance of highway bridges.

3.2. Nondestructive Methods for Condition Evaluation of Prestressing Steel Strands in Concrete Bridges – Final Report – Phase 1 – Technology Review

Author(s): AA. T. Ciolko and H. Tabatabai

Publication: NCHRP Web Document 23

Publication Date: March 1999

Abstract: This report contains the findings of a study performed to determine whether a practical and economical method for quantitative nondestructive condition evaluation of bonded prestressing systems in highway bridges exists. The report provides a comprehensive summary of a global technology review made to identify NDT methods developed in the time period commencing in 1990. The noted NDT advances of the decade, which possessed some potential for assessing strand condition, were characterized and evaluated based on technical, accuracy, operational, logistical, safety, and other factors. The contents of this report will be of interest to bridge maintenance engineers, researchers, and others concerned with assessing the condition of concrete bridges and the degree of strength and serviceability impairment created by deteriorating prestressing systems.

3.3. Ongoing Research - Adjacent Precast Box Beam Bridges: Connection Details

Author(s): Henry G. Russell

Publication: NCHRP Synthesis 20-05/ Topic 39-10 [Active (Synthesis)]

See: http://www.trb.org/trbnet/ProjectDisplay.asp?ProjectID=1673

First Meeting Date: September 2007

Second Meeting Date: June 2008

Scope: Bridges built with adjacent precast, prestressed concrete box beams are a popular and economical solution in many states because they can be constructed rapidly, and deck forming is eliminated. There is a new thrust to use these bridges for rapid construction under the Highways for LIFE program. According to recent National Bridge Inventory data, adjacent concrete box beams constitute about 17 percent of bridges built annually on public roads.

The box beams are generally connected by grout placed in a key between each of the units, and usually with transverse ties. Partial depth or full depth keys are typically used, incorporating grouts using various mixes. Transverse ties, grouted or un-grouted, vary from a limited number of threaded rods with finger tight nuts to several high strength tendons post-tensioned in multiple stages. In some cases, no topping is applied to the structure while in other cases a non-composite topping or a composite structural slab is added.

Bridges constructed using box beams have been in service for many years and have generally performed well. However, a recurring problem is cracking in the grouted joints between adjacent units, resulting in reflective cracks forming in the wearing surface. In most cases, the cracking leads to leakage which allows chloride laden water to saturate the sides and bottom of the beams, eventually causing corrosion of the non-prestressed and prestressed reinforcement. In severe cases, the joints crack completely and load transfer is lost. There is no design method for shear keys in the AASHTO Standard Specifications for Highway Bridges or the AASHTO LRFD Bridge Design Specifications. Most shear key details in use are regional “standard details” of uncertain origin, and there is no information on the magnitude of forces induced in the shear keys and the ability of a given detail to resist these forces.

This synthesis study will document the different types of grout key configurations, grouts, and transverse tie systems that are currently being used in the U.S. and Canada, and how each type has performed. The synthesis will include:

- Best practices and details that have proven to enhance the performance of box beam bridges
- Practices and details to avoid

- Specific areas of interest include the impact of the following-
    - Span range
    - Skew
    - Bearing types
    - Topped and non-topped
    - Phase construction
    - Waterproofing membranes
    - Exterior beam details, including connection to the barrier
- Grout specifications
- Inspection practices
- Means being used to maintain these bridge types, including rehabilitation and retrofitting techniques
- Sources of ongoing or completed analytical and/or experimental research pertaining to the design or construction of this type of bridges
- Design and/or construction issues that require further research and evaluation

This information will be gathered from state DOTs, other bridge owners, and industry. This will include Class 1 railroads and AREMA specifications. Information will be gathered by literature review (including state DOT standard details and specifications), surveys of state DOTS (through the AASHTO Highway Subcommittee on Bridges and Structures) and industry representatives (for example PCI), and interviews with selected individuals who may have in-depth information. Information on international practice may be included, if it is relevant.

Information gathered in this synthesis will provide a basis to understand the behavior of adjacent concrete beam bridges, and will help establish the most practical and efficient details to reduce maintenance costs and extend bridge service life.

4. Inspection and Repair Methodologies

A review of general inspection manuals was conducted to summarize the methods in use for assessing the condition of bridge members. In addition repair methods are included in this section.

4.1. SHRP-S-665 Concrete Bridge Protection and Rehabilitation: Chemical and Physical Techniques - Feasibility Studies of New Rehabilitation Techniques

Author(s): John G. Dillard, James O. Glanville, William D. Collins, Richard E. Weyers and Imad L. Al- Qadi

Publication: National Academy of Sciences

Publication Date: July 1993

Scope: The objective of this study was to examine and develop feasible chemical methods for the corrosion protection of reinforcing steel in concrete bridges. A broad spectrum of chemicals were evaluated, corrosion inhibitors, chloride scavengers, and polyaphrons. Screening tests were developed to evaluate inhibitor effectiveness and their ability to penetrate concrete. The evaluation of the inhibitors led to the recommendation of various types of inhibitors with potential application in reinforced concrete as well as 3 different treatment techniques. Reinforced concrete specimens were cast and subjected to repeated exposure to NaC1 solution and evaluated to investigate the inhibitors effectiveness after removing contaminated concrete. Corrosion progress was monitored by measuring half-cell potential, corrosion rate, and chloride concentration. When active corrosion was indicated, chloride contaminated concrete was removed to the rebar level through a grooving process. The grooves were chemically treated through solution ponding and backfilling with treated mortar. Seventeen treatments were evaluated. Mortar cubes were cast containing various treatment concentration and tested for compressive strength and resistivity. DCI, Alox 901, Cortec 1337, Cortec 1609, sodium tetraborate, and zinc borate were found effective in abating corrosion after concrete removal. However, both borate compounds cause set retardation. Polyaphrons were investigated as a possible corrosion preventor / reducer inhibitor. Carbon steel coupons were immersed in different polyaphron solutions. The cationic surfactant aphrons were found to be the most stable in the salt/pore solution environment. To study the diffusion rate of aphrons in concrete mixtures, concrete, mortar and cement paste specimens were cast. The results indicated that the diffusion rate of polyaphrons through various mixtures is very slow and therefore was not recommended as a practical concrete bridge treatment.

4.2. SHRP-S-360 Concrete Bridge Protection, Repair, and Rehabilitation Relative to Reinforcement Corrosion: A Methods Application Manual

Author(s): Richard E. Weyers, Brian D. Prowell, Michael M. Sprinkel, Michael Vorster

Publication: National Academy of Sciences

Publican Date: October 1993

Scope: This manual is intended as a practical guide for state highway agency personnel who are faced with the day-to-day task of cost-effectively protecting, repairing, and rehabilitating concrete bridges exposed to chloride-laden environments. As a practical guide, the manual addresses the chloride-induced corrosion of the reinforcing steel because the protection, repair, and rehabilitation methods presented are based on a working knowledge of the corrosion processes. Methods are presented to estimate the service life and remaining service life of

concrete bridge components. Economic models are presented to enable selection of the most cost-effective methods (i.e., those with minimum life-cycle cost) from the menu of protection, repair, and rehabilitation methods. These methods include standard physical, chemical, and experimental protection, repair, and rehabilitation methods. Each method is described with respect to limitations, estimated service life, estimated construction price or cost, construction procedures, quality assurance and construction inspection methods, and material performance specifications. In addition, rapid bridge deck protection, repair, and rehabilitation methods are presented. Two mechanized concrete removal methods, milling and hydrodemolition, are compared to the traditional method, pneumatic breakers. The three concrete removal methods are discussed with respect to labor- and capital-intensive operations, work characteristics, and quality management and control. The advantages of combining the strengths of the three removal methods are also presented.

4.3. Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges

Author(s): U.S. Department of Transportation Federal Highway Administration

Publication: FHWA-PD-96-001

Publication Date: December 1995 (Updated 2000)

This edition of the Recording and Coding Guide converts all units of measurement to the International System of Units. It also provides more thorough and detailed guidance in evaluating and coding specific bridge data.

4.4. Pontis Bridge Inspection Coding Guide

Author(s): Colorado Department of Transportation – Staff Bridge Branch

Publication Date: July 1997 (revision)

The Pontis Bridge Inspection Coding Guide was developed by the Staff Bridge Branch of the Colorado Department of Transportation. The July 1997 revision was made with input from CDOT bridge inspectors who had been performing bridge inspections using Pontis for approximately four years. The revision includes cross references to the General Comments and Definitions necessary to provide for uniform inspection reports from various bridge inspectors.

This Colorado version is intended to supplement the AASHTO Guide for Commonly Recognized (CoRe) Structural Elements with clarifying information and additional elements unique to Colorado bridges and structures. If conflicts occur between the guides, the AASHTO guide governs.

4.5. Bridge Safety Inspection Manual

Author(s): Commonwealth of Pennsylvania Department of Transportation

Publication: PennDOT Publication 238 - 2nd Edition

Publication Date: October 2002

Scope: The provisions of this Manual are intended for the safety inspection and management of bridges and culverts involving public roads in Pennsylvania. This Manual will provide guidance on the following aspects:

1. Responsibilities of various parties for bridge safety inspections
2. Technical standards and specifications for bridge inspection, load rating and posting

3. Administrative requirements to meet State and Federal regulations regarding recording and reporting inspection information

4.6. Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges

Author(s): U.S. Department of Transportation Federal Highway Administration

Publication: FHWA-1-M

Publication Date: 2003 1st Edition and 2005 Interim (PDF Unavailable)

This manual, formerly known as Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges, serves as a standard and provides uniformity in procedures and policies for determining physical condition, maintenance needs, and load capacity of the nation's highway bridges. It has been developed to assist bridge owners in establishing inspection procedures and evaluation practices that meet the National Bridge Inspection Standards (NBIS).

4.7. Condition Evolution in Bridge Management Systems and Corrosion-Induced Deterioration

Author(s): Guido Roelfstra, Rade Hajdin, Brian Adey, Eugen Brühwiler

Publication: Journal of Bridge Engineering, Vol. 9, No. 3, pp. 268-277

Publication Date: May 2004

Abstract: Condition assessment in the Swiss bridge management system (KUBA-MS) is performed on the element level. Five condition states are defined based on visual appearance. In order to forecast the condition states of any given element at any given time a relationship must be established between the element age and its condition state. This relationship, which describes the condition evolution, can be obtained empirically from statistical analysis of pairs of consecutive condition assessments (inspections). Markov chains are used in KUBA-MS to represent condition evolution and the transition probabilities are determined using regression analysis of pairs of inspections. Unfortunately there are almost no inspection data for the worst and second worst condition states. The forecasts made using Markov chains are therefore not always reliable. In this paper an alternative approach is suggested, which takes into consideration the physical phenomena underlying element deterioration. This alternative approach is applied to chloride-induced corrosion of steel reinforcement, by far the most common deterioration mechanism in Switzerland. The chloride-induced corrosion is modeled mathematically and numerical simulations of the condition evolution for different values of model parameters are performed. The simulation results have been mapped to condition states as defined in KUBA-MS and Markov transition matrices have been calibrated to fit simulation results.

5. Testing Methods Related to Corrosion of Metals

To assess the presence of corrosion of prestressing strands in concrete standardized testing methods have been developed. These test methods have been produced by both the American Association of State Highway Transportation Officials (AASHTO) and the American Society for Testing and Materials (ASTM). All methods related to determination, cause, or measurement of corrosion is summarized.

5.1. AASHTO T259-02: Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration

Scope: This method covers the determination of the resistance of concrete specimens to the penetration of chloride ion. It is intended for use in determining the effects of variations in the properties of concrete on the resistance of the concrete to chloride ion penetration. Variations in the concrete may include, but are not limited to, changes in the cement type and content, water-cement ratio, aggregate type and proportions, admixtures, treatments, curing, and consolidation. This test method is not intended to provide a quantitative measure of the length of service that may be expected from a specific type of concrete.

5.2. AASHTO T 260-97 (2005): Standard Method of Test for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials

Scope: This method covers procedures for the determination of the acid-soluble chloride ion content or the water-soluble chloride ion content of aggregates, portland cement, mortar or concrete.

5.3. AASHTO T277-05: Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration (PDF Unavailable)

Scope: AASHTO T 277-05 is identical to ASTM C1202-94 except provisions specified in this document. This test method covers the determination of the electrical conductance of concrete to provide a rapid indication of its resistance to the penetration of chloride ions. This test method is applicable to types of concrete where correlations have been established between this test procedure and long-term chloride ponding procedures such as those described in T 259.

5.4. ASTM C 114 - 07: Standard Test Methods for Chemical Analysis of Hydraulic Cement (Active)

Scope: These test methods cover the chemical analyses of hydraulic cements. Any test methods of demonstrated acceptable precision and bias may be used for analysis of hydraulic cements, including analyses for referee and certification purposes, as explained in Section 3. Specific chemical test methods are provided for ease of reference for those desiring to use them. They are grouped as Reference Test Methods and Alternative Test Methods. The reference test methods are long accepted classical chemical test methods which provide a reasonably well-integrated basic scheme of analysis for hydraulic cements. The alternative test methods generally provide individual determination of specific components and may be used alone or as alternates and determinations within the basic scheme at the option of the analyst and as indicated in the individual method.

5.5. ASTM C457 - 08b Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete

Scope: This test method describes procedures for microscopical determinations of the air content of hardened concrete and of the specific surface, void frequency, spacing factor, and paste-air ratio of the air-void system in hardened concrete (1). Two procedures are described:

- Procedure A, the linear-traverse method
- Procedure B, the modified point-count method

5.6. ASTM C 597-02: Standard Test Method for Pulse Velocity Through Concrete (Active)

Scope: This test method covers the determination of the propagation velocity of longitudinal stress wave pulses through concrete. This test method does not apply to the propagation of other types of stress waves through concrete.

5.7. ASTM C 856 - 04 Standard Practice for Petrographic Examination of Hardened Concrete (Active)

Scope: This practice outlines procedures for the petrographic examination of samples of hardened concrete. The samples examined may be taken from concrete constructions, they may be concrete products or portions thereof, or they may be concrete or mortar specimens that have been exposed in natural environments, or to simulated service conditions, or subjected to laboratory tests. The phrase "concrete constructions" is intended to include all sorts of objects, units, or structures that have been built of hydraulic cement concrete.

5.8. ASTM C 876 – 91 (1999): Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete (Active)

Scope: This test method covers the estimation of the electrical half-cell potential of uncoated reinforcing steel in field and laboratory concrete, for the purpose of determining the corrosion activity of the reinforcing steel.

5.9. ASTM C 1152/C 1152M – 04 e1: Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete (Active)

Scope: This test method provides procedures for the sampling and analysis of hydraulic-cement mortar or concrete for chloride that is acid soluble under the conditions of test. In most cases, acid-soluble chloride is equivalent to total chloride.

5.10. ASTM C 1202 - 07: Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration (Active)

Scope: This test method covers the determination of the electrical conductance of concrete to provide a rapid indication of its resistance to the penetration of chloride ions. This test method is applicable to types of concrete where correlations have been established between this test procedure and long-term chloride ponding procedures such as those described in AASHTO T 259.

5.11. ASTM C 1218 – 99(2008): Standard Test Method for Water-Soluble Chloride in Mortar and Concrete (Active)

Scope: This test method provides procedures for the sampling and analysis of hydraulic-cement mortar or concrete for chloride that is water soluble under the conditions of test.

5.12. ASTM C 1383 – 04: Standard Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method (Active)

Scope: This test method covers procedures for determining the thickness of concrete slabs, pavements, bridge decks, walls, or other plate-like structure using the impact-echo method.

5.13. ASTM D 4580 – 03(2007) Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding (Active)

Scope: This practice covers procedures for surveying concrete bridge decks by sounding to determine delaminations in the concrete. It is not intended that the procedures described herein

are to be used on bridge decks that have been overlaid with bituminous mixtures. The procedures may be used on bridge decks that have been overlaid with Portland cement concrete mixtures; however, areas indicated to be delaminated may have a lack of bond between the overlay and the underlying bridge deck.

5.14. ASTM D 6087 – 07 Standard Test Method for Evaluating Asphalt-Covered Concrete Bridge Decks Using Ground Penetrating Radar (Active)

Scope: This test method covers several radar evaluation procedures that can be used to evaluate the condition of concrete bridge decks overlaid with asphaltic concrete wearing surfaces. Specifically, this test method predicts the presence or absence of concrete or rebar deterioration at or above the level of the top layer of reinforcing bar.

5.15. ASTM G 1 - 03: Standard Practice for Cleaning and Evaluating Corrosion Test Specimens.

Scope: This practice covers suggested procedures for preparing bare, solid metal specimens for tests, for removing corrosion products after the test has been completed, and for evaluating the corrosion damage that has occurred. Emphasis is placed on procedures related to the evaluation of corrosion by mass loss and pitting measurements. (Warning - In many cases the corrosion product on the reactive metals titanium and zirconium is a hard and tightly bonded oxide that defies removal by chemical or ordinary mechanical means. In many such cases, corrosion rates are established by mass gain rather than mass loss.)

5.16. ASTM G 4 - 01 (2008): Standard Guide for Conducting Corrosion and Coupon Tests in Field Applications

Scope: This guide covers procedures for conducting corrosion tests in plant equipment or systems under operating conditions to evaluate the corrosion resistance of engineering materials. It does not cover electrochemical methods for determining corrosion rates.

5.17. ASTM G 5 – 94 (1999) e1: Standard Reference Test Method for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements

Scope: This test method describes an experimental procedure for checking experimental technique and instrumentation. If followed, this test method will provide repeatable potentiostatic and potentiodynamic anodic polarization measurements that will reproduce data determined by others at other times and in other laboratories provided all laboratories are testing reference samples from the same lot of Type 430 stainless steel.

5.18. ASTM G 15 - 08: Standard Terminology Relating to Corrosion and Corrosion Testing

Scope: This terminology covers commonly used terms in the field of corrosion. Related terms may be found in Terminologies D 16, D 4538, G 40, or other ASTM terminology standards. All terms defined by ASTM committees may be found in the *ASTM Dictionary of Engineering Technology*.

5.19. ASTM G 16 - 95 (2004): Standard Guide for Applying Statistics to Analysis of Corrosion Data

Scope: This guide presents briefly some generally accepted methods of statistical analyses which are useful in the interpretation of corrosion test results.

5.20. ASTM G 46 – 94 (2005): Standard Guide for Examination and Evaluation of Pitting Corrosion

Scope: This guide is intended to assist in the selection of procedures that can be used in the identification and examination of pits and in the evaluation of pitting (See Terminology G15) corrosion to determine the extent of its effect.

5.21. ASTM G 48 - 03: Standard Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys By Use of Ferric Chloride Solution

Scope: These test methods cover procedures for the determination of the resistance of stainless steels and related alloys to pitting and crevice corrosion (see Terminology G 15) when exposed to oxidizing chloride environments. Six procedures are described and identified as Methods A, B, C, D, E, and F.

Method A- Ferric chloride pitting test.

Method B- Ferric chloride crevice test.

Method C- Critical pitting temperature test.

Method D - Critical crevice temperature test.

Method E - Critical pitting temperature test for stainless steels.

Method F - Critical crevice temperature test for stainless steels.

5.22. ASTM G 49 - 85 (2005): Standard Practice for Preparation and Use of Direct Tension Stress Corrosion

Scope: This practice covers procedures for designing, preparing, and using ASTM standard tension test specimens for investigating susceptibility to stress-corrosion cracking. Axially loaded specimens may be stressed quantitatively with equipment for application of either a constant load, constant strain, or with a continuously increasing strain.

5.23. ASTM G 61 – 86 (2003) e1: Standard Test Method for Conducting Cyclic Potentiodynamic Polarization Measurements for Localized Corrosion Susceptibility of Iron-, Nickel or Cobalt Based Alloys

Scope: This test method gives a procedure for conducting cyclic potentiodynamic polarization measurements to determine relative susceptibility to localized corrosion (pitting and crevice corrosion) for iron-, nickel-, or cobalt-based alloys in a chloride environment. This test method also describes an experimental procedure which can be used to check one's experimental technique and instrumentation.

5.24. ASTM G 102 – 89 (2004) e1: Standard Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements

Scope: This practice is intended to provide guidance in converting the results of electrochemical measurements to rates of uniform corrosion. Calculation methods for converting corrosion current density values to either mass loss rates or average penetration rates are given for most engineering alloys. In addition, some guidelines for converting polarization resistance values to corrosion rates are provided.

5.25. ASTM G 108 – 94 (2004) e1: Standard Test Method for Electrochemical Reactivation (EPR) For Detecting Sensitization Of AISI Type 304 And 304L Stainless Steel

Scope: This test method describes a laboratory procedure for conducting an electrochemical reactivation (EPR) test on AISI Type 304 and 304L (UNS No. S30400 and S30403, respectively) stainless steels. This test method can provide a nondestructive means of quantifying the degree

of sensitization in these steels (1, 2, 3). This test method has found wide acceptance in studies of the effects of sensitization on intergranular corrosion and intergranular stress corrosion cracking behavior (see Terminology G15). The EPR technique has been successfully used to evaluate other stainless steels and nickel base alloys (4), but the test conditions and evaluation criteria used were modified in each case from those cited in this test method.

5.26. ASTM G 109 - 07: Standard Test Method for Determining the Effects of Chemical Admixtures on the Corrosion of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments.

Scope: This test method covers a procedure for determining the effects of chemical admixtures on the corrosion of metals in concrete. This test method can be used to evaluate materials intended to inhibit chloride-induced corrosion of steel in concrete. It can also be used to evaluate the corrosivity of admixtures in a chloride environment.

5.27. ASTM G 142 – 98 (2004): Standard Test Method for Determination of Susceptibility of Metals to Embrittlement in Hydrogen Containing Environments at High Pressure, High Temperature, or Both.

Scope: This test method covers a procedure for determination of tensile properties of metals in high pressure or high temperature, or both, gaseous hydrogen-containing environments. It includes accommodations for the testing of either smooth or notched specimens.

6. Bridge Deterioration Reports

A number of prestressed concrete bridge systems have experienced significant damage as a result of corrosion. The observed damage ranges from cracking, rust stains, and spalling, to complete collapse. This has occurred within the U.S. as well as in other countries. This chapter summarizes the previous studies conducted on damaged bridge systems.

6.1. Evaluation of Keyway Grout Test Methods for Precast Concrete Bridges

Author(s): Gulyas, R. J.; Wirthlin, Gregory J.; Champa, Jeffrey T.

Publication: PCI Journal, Vol. 40, No. 1, pp. 44-57

Publication Date: January-February 1995

Scope: Precast, prestressed concrete box beams, bulb tees, and voided slabs are used in short-to-medium span bridges. These bridge elements have grouted keyway sections to transfer the vertical shear forces between adjacent elements. The keyways are filled with differing types of non-shrink grouts. By definition, these non-shrink grouts do not have requirements for maximum shrinkage limits or minimum bond strength. Both properties are critical for effective load transfer. In the field, leaking keyways and vertical faulting of keyways have been reported. A laboratory study was undertaken to compare component material tests and composite grouted keyway specimens using two different grouting materials: non-shrink grouts and magnesium ammonium phosphate mortars. Comparative composite specimens were tested in vertical shear, longitudinal shear, and direct tension. Results indicate significant differences in performance between the materials. Composite testing of the grouted keyway assemblies, rather than component materials testing, was shown to be a more accurate way to evaluate the performance of the grouting material

6.2. Full-Scale Testing of Shear Keys for Adjacent Box Girder Bridges

Author(s): Miller, R. A.; Hlavacs, George M.; Long, Todd; Greuel, Andreas

Publication: PCI Journal, Vol. 44, No. 6, pp. 80-90

Publication Date: November 1999

Scope: Adjacent precast, prestressed box girder bridges are widely used in the United States, but the shear keys between the girders tend to crack and leak. Three different shear key configurations were studied, i.e., a current detail where the shear key is approximately 10 in. (250 mm) from the top of the girder and grouted with non-shrink grout, this same detail grouted with epoxy rather than non-shrink grout, and a proposed mid-depth keyway grouted with non-shrink grout. The tests were conducted on a full-scale, four-beam assembly which represented part of a bridge. The results showed that the currently used shear key detail cracks due to thermal stresses generated as the beams deflect upward and downward due to daily heating and cooling. The mid-depth shear key is less susceptible to these stresses and was found to be more resistant to cracking. The epoxied shear keys did not crack. Loading did not appear to cause new cracking, but rather seemed to propagate existing thermal cracks.

6.3. Test to Failure of a 54ft. Deteriorated Pretensioned Precast Concrete Deck Beam

Author(s): Neil M Hawkins, Juan. B. Fuentes

Publication: Illinois Transportation Engineering Series, No.118, Series 281

Publication Date: May 2002

Abstract: A 54-ft. long, 27 inch deep, deteriorated pretensioned deck beam was taken from an existing bridge and tested to failure under equal loads applied 7-ft either side of its midspan. A systematic visual condition assessment was made of the beam before testing. After testing, the concrete cover over the strands was removed and their condition assessed. The beam was sawn in half at the failure location and the section geometry recorded. Concrete and strand samples were recovered and their mechanical properties measured. The stiffness of the beam before cracking equaled that calculated using the measured properties of the cross-section and neglecting any damage due to local deterioration. The moment for first cracking equaled that calculated using the weakest section within the constant moment region. However, that cracking was confined to the most deteriorated location. A marked stiffness change did not occur until general cracking at a moment that equaled the cracking moment calculated neglecting any strand corrosion. The immediate post-cracking stiffness also agreed with that calculated neglecting any strand corrosion. The load for failure was 4% less than that calculated using the measured properties of the weakest section and the number of non-corroded strands. The beam failed by crushing of the concrete in the compression face near midspan. The deflection for failure was only 40% of the expected deflection for the number of strands found to be effective at the load for failure.

6.4. Structural Condition Assessment and Service Load Performance of Deteriorated Pretensioned Deck Beam Bridges

Author(s): Neil M Hawkins, Juan. B. Fuentes

Publication: Illinois Transportation Engineering Series, No.124, Series 285

Publication Date: May 2003

Abstract: Three 30-year old deteriorated pretensioned deck beams were removed from an existing bridge in Illinois and re-assembled in the laboratory into a bridge sub-assemblage. Non-destructive and destructive tests and evaluations of the three beams were made in three phases:(1) Detailed visual condition assessment of the as-delivered beams; (2) The service load performance under truck type loadings of a bridge sub assemblage constructed with three beams and (3) The strength and ductility of the individual beams tests to failure. Detailed descriptions are provided of the test results of each study of deterioration assessment made by two contractors, of coupon tests on prestressing steel and concrete samples taken from the beams, and of chloride profiles measured through the soffit and sides of the beams. Theoretical aspects of the response of deck beam bridges, including the modeling of the response of sub assemblage were studied. A method based on the beam on elastic foundation theory was developed to replicate the effects of changing the stiffness of the longitudinal joint between the beams. Using that procedure bending moments in individual beams along and across the width of a bridge, inter girder shear forces and assemblage. With that method appropriate load distribution factors for deteriorated existing deck beam bridges can be calculated. The condition of the transverse tie rod was found to be critical to service load performance. Cracking of the longitudinal joint had a little effect on the stiffness of a bridge provided the transverse tie rod was snug. However, loss of snugness with time or corrosion increased substantially the potential for overloading a deteriorated beam.

6.5. Field Inspection and Forensic Investigation of the SR 1014 Lake View Drive Bridge over Interstate 70 Final Report

Author(s): Raymond Hartle

Publication: Michael Baker, Jr. Report, p.52

Publication Date: April 2006

Abstract: At approximately 6:00 PM on Tuesday, December 27, 2005, the Department received reports that the SR1014 Lake View Drive Bridge had partially collapsed onto Interstate 70. The collapsed portion consisted of Beam 1 in Span 3 over the eastbound lanes of I-70, which is the north elevation fascia beam. The reinforced concrete bridge parapet and metal railing of Span 3 also fell with the beam. On Wednesday, December 28, 2005 at approximately 6:30AM, Baker was notified to go to the site and assist PennDOT personnel. The report outlines the observations of the field inspection and forensic examination of the failed beam.

6.6. Full-scale Testing Program on De-Commissioned Girders from the Lake View Drive Bridge

Author(s): Kent A. Harries

Publication: PITT report CE/ST-33

Publication Date: August 2006

Pages: 148

Abstract: On the evening of December 27th, 2005 the fascia beam supporting the east side parapet wall of the third span of the Lakeview Drive Bridge failed under the action of dead load. The span is an 89'-10" long prestressed adjacent box girder structure comprised of eight 42" deep by 48" wide girders. Given that other similar bridges exist in the surface transportation system of the Commonwealth, there was an interest in understanding the failure and improving the assessment of reserve capacities of this type of bridge; particularly those with 40 or more years of service. A multi-aspect study was undertaken and is reported. The objective of this study was to provide guidance with respect to conducting inspections and load rating of similar structures.

Load tests were conducted on two individual girders- an interior and an exterior girder- recovered from the Lakeview Drive Bridge. This report summarizes the test preparation, including an extensive pre-test inspection, test protocols and reports all test results. Additionally, the results of a parallel acoustic emissions instrumentation scheme conducted by Physical Acoustics Corporation are presented. Finally, observations from an extensive post-test forensic evaluation of the test girders are presented.

Accompanying the physical testing, an extensive analytical study of the box girder sections was conducted using both advanced sections analysis tools and three-dimensional finite element modeling techniques. The parameters considered in this study include a) the loss of prestressing strand due to corrosion or mechanical damage; b) the presence of the barrier wall; c) the presence of gaps (expansion joints) in the barrier wall; d) thickness of the girder webs; and e) the effect of girder depth (a 27" by 48" girder was also considered). A sound and relatively simple methodology for load rating asymmetric box girders is presented and verified against the physical test results. Simple equations are also provided for rapid assessment of such structures.

Conclusions and recommendations based on the study objectives are presented.

6.7. Forensic Evaluation of Prestressed Box Beams from the Lake View Drive Bridge Over I-70

Author(s): Clay Naito, Richard Sause, Ian Hodgson, Stephen Pessiki, Chintan Desai

Publication: ATLSS Report No. 06-13

Publication Date: September 2006

Abstract: On December 27, 2005 the east-side fascia beam of the Lakeview Drive over I-70 Bridge in Washington Pennsylvania, failed near midspan and fell to the highway below. No impact from traffic on the highway below or overload of the bridge itself was reported. Inspection of the bridge revealed heavy spalling and corrosion of the strands on the bottom flange of the failed noncomposite prestressed concrete box beam member. Additional corrosion was revealed on other box beams and the bridge was subsequently removed from service. This report summarizes a forensic investigation conducted on a number of the beams from the Lakeview Drive over I-70 Bridge. The investigation includes a summary of in-situ material properties, as-built member dimensions, remaining prestress, chloride profile in the webs and flanges of the box beams, depth of carbonation, concrete quality, and a detailed photographic summary of external the corrosion and spalling conditions and the corresponding level of internal damage. The forensic investigation indicated that the beams were built close to the design specifications. The concrete strength, and quality (air void spacing, aggregate gradation, aggregate type, etc.) were within specifications. The prestressing strand had the required tensile capacity. The web thicknesses varied, suggesting that the void forms shifted when the beams were cast. The approved shop drawings had two features not common with current construction techniques: (1) the bottom layer of prestressing strand was not contained within stirrups; (2) the required cover to the bottom layer of strands was less than 1.5-in. In addition, field inspection revealed the presence of vent holes in the top flange of the box beams. In a number of box beams this resulted in water from the bridge deck entering and remaining in the void region. A sample of the trapped water indicated a high chloride level. Chloride levels through the concrete beam webs and flanges were measured. Elevated chloride levels were measured in the outside surface of the bottom flange beams. These chloride levels decreased through the thickness of the flange, but in some cases increased again near the top (inside) surface of the bottom flange. The forensic investigation indicated that strand cover on some strands were lower than the required values. The chloride level in the concrete at the lower layer of strands was typically high enough that corrosion would be expected.

6.8. Analysis of Recent Bridge Failures in the United States

Author(s): Kumalasari Wardhana, Fabian C. Hadipriono

Publication: Journal of Performance of Constructed Facilities, Vol. 17, No. 3, pp. 144-150

Publication Date: August 2003

Abstract: Over 500 failures of bridge structures in the United States between 1989 and 2000 were studied. The age of the failed bridges ranged from 1 year (during construction) to 157 years, with an average of 52.5 years. The most frequent causes of bridge failures were attributed to floods and collisions. Flood and scour, with the major flood disaster in 1993, contributed to the frequency peak of bridge failures (almost 53% of all failures). Bridge overload and lateral impact forces from trucks, barges/ships, and trains constitute 20% of the total bridge failures. Other frequent principal causes are design, detailing, construction, material, and maintenance. Comparison made among three periods of similar studies (1977–1981, 1982–1988, and 1989–2000) revealed almost similar trends, with most failures occurring during the bridge's service life. Also, human-induced external events occurred frequently in all three periods, but were most dominant in the first and third periods. Technological advances in information systems have a great impact on data collection and analysis.

6.9. Prestressed Concrete Box Beam Bridges- Two DOTS' Experience

Author(s): Thomas P. Macioce, Harold C. Rogers, Ralph Anderson, D. Carl Puzey

Publication: 2007 PCI-FHWA National Bridge Conference Sessions (83)

Publication Date: October 2007

Abstract: The prestressed concrete box beam bridge is a common superstructure type in the nation's bridge inventory. Two of the most prevalent superstructure types are adjacent and spread box beam bridges. Prestressed box beam bridges were first constructed in the late 1950's and early 1960's. The design, fabrication and construction techniques have evolved from the first generation beams to today's standards. Early and current details from the Pennsylvania Department of Transportation and Illinois Department of Transportation will be presented.

The in-service performance of prestressed box beams will be discussed. Results from investigations have lead to revised design and construction details, inspection and load rating analysis methods used by Pennsylvania DOT and Illinois DOT.

6.10. Deterioration of Prestressed Concrete Bridge Beams

Author(s): S.M. Bruce, P.S. McCarten, S.A. Freitag, L.M. Hasson

Publication: Land Transport New Zealand Research Report 337

Publication Date: 2008

Pages: 72

Abstract: A routine inspection revealed significant corrosion of the prestressing strand on a concrete road bridge built in 1966 to a standard design used in about 117 State Highway bridges in New Zealand. To identify the cause of the deterioration and how many bridges of this design might be affected, the conditions of 29 similar bridges on New Zealand State Highways were evaluated by site investigation. The research, carried out in 2005–2006, found that although the concrete quality in the bridge beams was generally good, the combination of cover depths less than 25 mm and exposure to salt spray had increased the likelihood of corrosion in bridges of this design in the B2 (coastal frontage) exposure zone. Bridges in the B1 (coastal perimeter) and A2 (inland) zones are less likely to be affected, although the concrete in some of the beams contained chlorides added during construction. The risk associated with prestressing corrosion in this beam design is higher than in current designs because the prestressing strand is poorly confined and the cover depth is low. Bridges of this design in the B2 zone will probably need some form of intervention to remain serviceable for a 100-year service life.

7. General Study of Prestressing Steel Damage in Concrete

This chapter summarizes research conducted on general corrosion of steel in concrete. This encompasses a broad category. Included in the references are studies on the corrosion process, mitigation methods, crack formation associated with corrosion, modeling of cracking, and the implications of damage on strength. The references are presented in order of their publication date.

7.1. Mitigation of Corrosion in Concrete Bridges

Author(s): Paul Virmani, John M. Hooks

Publication: www.**pwri.go.jp**/eng/ujnr/tc/g/pdf/19/3-1hooks.pdf

Publication Date: Unknown

Abstract: The deterioration of various concrete bridge components built in the past with black steel reinforcement is one of the most common, most damaging and most costly problems facing bridge owners in the United States. The major cause of concrete deterioration (cracking, delamination, and spalling), is the corrosion of embedded black steel reinforcing bars as a result of chloride ions (permeating through the concrete cover) in combination with moisture and oxygen. The average black steel reinforced concrete (R/C) bridge deck, in a snow belt State, showed spalling in about 7-10 years. Although prestressed concrete (PS/C) bridge members are generally cast with good control of mix designs and curing regimes, they are still vulnerable to corrosion (of the pretensioned, uncoated strands) similar to that of the black steel in reinforced concrete, albeit after a longer period of service. Since PS/C members rely on the tensile strength of the strands to resist loads, loss of a few strands per member could be catastrophic. Even small corrosion pits cause fracture of a strand, as compared to non-prestressed concrete reinforcing that will literally rust away without breaking.

For post-tensioned concrete (PT/C) bridge members (both external and internal prestressing), the voids in grouted ducts and/or excessive bleed water (in certain grout mix designs), in addition to chloride/water entering the rough breached ducts or faulty joints at anchorage locations, will corrode the uncoated strands. The underlying difficulty is that there are no reliable, rapid and cost-effective non-destructive methods to assure owners that completed PT/C structures have met the construction specifications. One of the major inspection concerns is whether the ducts in PT/C members have been completely filled with grout and whether there is a uniform coverage over the prestressing steel. Many times, it has been found invariably that the ducts have large voided sections and were only filled partially with grout. In addition, it is very difficult to assess the condition of anchorage areas. Past research has identified that excessive bleed water in certain commercial grouts corroded the strands in a very short time, and that in due time under load, these corroded strands can break prematurely. Since PS/C members rely on the tensile strength of the strand to resist loads, loss of a few strands in members could be catastrophic. Even small pits lead to fracture of a strand, as compared to R/C concrete where the reinforcing will literally rust away (if preventative measures are not taken) without breaking.

This paper summarizes the status of various corrosion protection systems in use for construction and rehabilitation with advantages, limitations, issues and concerns for their use to provide cost effective solutions in controlling corrosion in concrete bridges in the United States.

7.2. Prestressed Bridges and Marine Environment

Author(s): Vladimir Novokshchenov

Publication: Journal of Structural Engineering, Vol. 116, No. 11, pp.3191-3205

Publication Date: November 1990

Abstract: A study was made of the corrosion of prestressing steel in bridge components exposed to a marine environment using analytical procedures and available techniques developed for conventional reinforced concrete structures. Four bridges were examined. Based on results of the study, it appears that in a marine environment the seawater and the seawater spray are major carriers of sufficient chloride salts to cause corrosion of prestressing steel. The atmosphere surrounding a bridge is not aggressive enough to cause any noticeable corrosion-related distress in bridge members. The primary pathway for the ingress of chloride ions is through a concrete cover, sheathing, and grouting. Chlorides may also be deposited on the surface of a deck slab by vehicle tires and later washed down through deficient expansion/contraction joints to anchorages and tendons in end areas of pre- and posttensioned girders. Among major factors affecting the extent of corrosion-related distress in prestressed bridge members are the following: time of exposure to direct action of the seawater, concentration of chlorides at the level of reinforcement, condition of expansion/contraction joints, permeability of concrete, thickness of concrete cover, quality of grouting, as well as the type of sheathing in prestressing tendons.

7.3. Evaluation of Degree of Rusting on Prestressed Concrete Strand

Author(s): Sason, Augusto S.

Publication: PCI Journal, Vol. 37, No. 3, pp. 24-30

Publication Date: June 1992

Abstract: Presents a procedure for classifying the degree of rust on a piece of prestressing strand and discusses the reasons for acceptance or rejection of each classification. Visual standards are developed by which inspectors can identify the degree of corrosion at which pitting occurs.

7.4. Corrosion Cracking in Relation to Bar Diameter, Cover, and Concrete Quality

Author(s): Rasheeduzzafar, S. S. Al-Saadoun, A. S. Al-Gahtani

Publication: Journal of Structural Engineering, Vol. 4, No. 4, pp. 327-342

Publication Date: November 1992

Abstract: Concrete cover, concrete quality, and bar size have a significant effect on corrosion initiation and corrosion cracking. This paper attempts to quantify the effect of these three parameters in providing corrosion protection to reinforcing steel. It is found that the cover-to-bar-diameter (c/d) ratio is a more definitive protection parameter against corrosion cracking than either cover or bar diameter separately. In view of the importance of c/d ratio, clear cover specifications without consideration of the bar size leads to inadequate and misleading design for corrosion protection, especially in concrete where internal chlorides are present in concrete from the time of manufacturing, making the corrosion propagation time prior to cracking an important phase in the service life of structures. A concept of corrosion cracking resistance factor, cf/d or c/dw incorporating cover, bar diameter, and concrete quality either in terms of strength (f) or water-cement ratio (w) has been developed to quantify the relative corrosion protection provided by a particular set of detailing and strength parameters.

7.5. Influence of Service Cracking on Reinforcement Steel Corrosion

Author(s): François. R; Arliguie.G

Publication: Journal of materials in civil engineering, Vol. 10, No. 1, pp. 14-20 (27 ref)

Publication Date: February 1998

Abstract: The purpose of this publication is to determine the relationship between cracking in the loaded reinforced concrete and corrosion of embedded steel in a chloride environment. This paper deals with the synthesis carried out over a 12-year period on reinforced concrete elements kept in a loading state, in a confined salt fog. Test specimens were 3-m-long beams, which is a sufficient size to be representative of the actual operating conditions of reinforced concrete structures. The development of corrosion in concrete specimens was assessed by recording the development of secondary cracking. The interpretation of the results obtained on the different type of beams allowed one to conclude that the development of reinforcement corrosion is not influenced by the widths of cracks (for widths less than 0.5 mm) or by the crack itself. The results appear to indicate that the load applied to a reinforced concrete beam plays an important role in the penetration of aggressive agents and then in the corrosion of the reinforcement.

7.6. The Inhibitive Effects of Electrochemical Treatment Applied To Steel in Concrete

Authors: G. K. Glass, N. R. Buenfeld

Publication: Corrosion Science Volume 42, Issue 6, Pages 923-927.

Publication Date: June 2000

Abstract: It has been postulated that the ability of hydrated cement paste to resist a fall in pH at high pH values is one of its most important inhibitive properties, while the most important factor affecting the initiation of corrosion in chloride contaminated concrete is entrapped air voids. Air voids prevent the local formation of a calcium hydroxide rich layer at the steel surface. Such an inhibitive layer minimises the risk of corrosion initiation at relatively high chloride contents (typically 1.5% by weight of cement). This work considers the effectiveness of electrochemical treatment to produce an inhibitive layer at the steel-concrete interface. This method may be applied as a preventative measure to decrease the risk of corrosion initiation resulting from subsequent chloride contamination.

7.7. Synergistic Effect of Corrosion Inhibitor and Inorganic Coating on Reinforcement Corrosion

Author(s): G. Batis, P. Pantazopoulou, A. Routoulas

Publication: Anti-corrosion Methods and Materials, Vol. 48, No. 2, pp. 107 - 115

Publication Date: 2001

Abstract: Concrete surface coatings, either organic or inorganic, have long been used for the protection of reinforced concrete. The aim of the present work was to compare, in the presence of chloride ions, the performance of an acrylic emulsion and an inorganic coating, when the latter is or is not combined with an inorganic corrosion inhibitor. The behavior of the inorganic coating was examined, as its use is increasing due to environmental reasons and it can be applied on concrete surfaces for the rehabilitation of old structures. Strain gauge (SG) technique, half-cell potential measurements, mass loss and carbonation depth measurements, as well as chloride diffusion rate, revealed that the acrylic emulsion provides better protection for reinforcing steel in concrete than the inorganic coating. However, the combination of the inorganic coating with the corrosion inhibitor provides a higher level of protection against steel bar corrosion.

7.8. Evaluation of Corrosion Protection for Internal Prestressing Tendons in Precast Segmental Bridges

Author(s): Jeffrey S. West, John E. Breen, René P. Vignos

Publication: PCI Journal, Vol. 47, No. 5, pp. 76-91

Publication Date: September 2002

Abstract: A research program utilizing modified macrocell corrosion specimens was conducted to investigate corrosion protection for internal tendons in segmental bridges. Test variables were segmental joint type, duct type, joint precompression and grout type. Specimens were subjected to 4 years of exposure testing, after which selected specimens were removed for destructive examination. Dry joint specimens performed very poorly, as evidenced by corrosion currents measured during exposure testing and by tendon and duct corrosion observed upon destructive examination. Epoxy joints limited chloride penetration, preventing tendon corrosion and reducing duct corrosion. Plastic post-tensioning ducts performed very well, limiting strand corrosion to negligible levels. The research indicates that epoxy joints are required for the protection of internal tendons in aggressive environments, and that plastic post-tensioning ducts provide a significant improvement in tendon corrosion protection. Many of the conclusions and recommendations presented are not only specific to segmental construction but are applicable to all forms of internal, grouted post-tensioning tendons.

7.9. Life-Cycle Modeling of Corrosion-Affected Concrete Structures: Propagation

Author(s): C. Q. Li

Publication: Journal of Structural Engineering, Vol. 129, No. 6, pp. 753-761

Publication Date: June 2003

Abstract: Although research in reinforcement corrosion in concrete has been intensive for the past three decades, studies of the most recently published literature reveal that the current state of research in corrosion propagation and its effects on structural resistance deterioration remains unsatisfactory. The intention of this paper is to develop models of structural resistance deterioration used in whole life performance assessment of corrosion-affected concrete structures. An assessment criterion is established to define the structural performance in terms of strength and serviceability limit states. A comparison of the experimental results on strength deterioration as determined from destructive load test and nondestructive measurement of corrosion current density is undertaken. From the developed models, life cycles of corrosion-affected concrete structures are determined in the paper. Together with previous results, a complete picture of whole life performance assessment of corrosion-affected reinforced concrete structures is depicted. The methodology presented in the paper can be used as a tool for structural engineers and asset managers in assessing concrete infrastructure and making decisions with regard to its maintenance and rehabilitation.

7.10. Analyzing Crack Width to Predict Corrosion in Reinforced Concrete

Author(s) T. Vidal, A. Castel, R. Francois:

Publication: Cement and Concrete Research, Vol. 34, No. 1, pp. 165-174

Publication Date: January 2004

Abstract: Our aim in this paper is to introduce a set of relationships linking the distribution of reinforcement corrosion and the width of cover crack that results from such corrosion. This work is based on experimental results obtained on the longitudinal reinforcements of two beams naturally corroded over periods of 14 and 17 years. We first compared these experimental results with existing models linking crack width and attack penetration. Noting that such models only

partially predict actual experimental data, we put forward a new model using the parameter of reinforcement cross-section loss.

7.11. Reliability Based Service Life Prediction of Corrosion Affected Concrete Structures

Author(s): Chun Qing Li

Publication: Journal of Structural Engineering, Vol.130, No. 10, pp.1570 - 1577

Publication Date: October 2004

Abstract: A review of the most recently published literature suggests that the prediction of service life of corrosion affected concrete structures remains at the stage of parametric studies, in spite of intensive research on reinforcement corrosion in concrete structures for the past three decades or so. The intention of this paper is to present a performance-based methodology for service life prediction of corrosion affected concrete structures and apply it to flexural members in marine environments. Reliability methods are employed to determine the time period for each phase of service life. It is found that corrosion induced concrete cracking would occur in reinforced concrete flexural members at about 18% of its total service life, and that, once reinforced concrete flexural members become unserviceable due to corrosion induced excessive deflection, there is about 13% of the service life remaining before the structures finally become unsafe. It is concluded that the methodology presented in this paper can serve as a rational tool for decision makers with regard to repairs and strengthening of corrosion affected concrete structures. Accurate prediction of each phase of service life of corrosion affected structures can assist structural engineers and asset managers in achieving a cost-effective strategy in the management of reinforced concrete infrastructures.

7.12. Deterioration of Reinforced Concrete Structures due to Chemical–Physical Phenomena: Model-Based Simulation

Author(s): Anna V. Saetta

Publication: Journal of Materials of Civil Engineering, Vol. 17, No. 3, pp. 313-319

Publication Date: May 2005

Abstract: The deterioration process of reinforced concrete structures due to chemical–physical phenomena can be profitably analyzed by means of model-based simulations, performed by using a mathematical/numerical approach. In this work both the model of humidity, pollutant and temperature diffusion, and the mechanical damage approach have been applied to some real cases with the aim of establishing a possible develop-line for the analysis of degradation that can be applied to real engineering structures. The intend is the evaluation of the structural safety and the prediction of the expected service life of reinforced concrete structures.

7.13. Performance of Coated Reinforcing Bars in Cracked Bridge Decks

Author(s): F. Fanous, H. Wu

Publication: Journal of Structural Engineering, Vol. 10, Issue 3, pp. 255-261

Publication Date: May 2005

Abstract: The presence of cracks in bridge decks that are reinforced with epoxy-coated reinforcing (ECR) bars has raised some concerns among bridge and maintenance engineers in the state of Iowa. To study the effects of deck cracking on the performance of ECR bars, several concrete cores that contained reinforcing bars were collected from 80 bridges that are located in different counties throughout the state of Iowa. These samples were collected from cracked and

uncracked areas of the bridge decks. Concrete powder samples were collected from these cores and were analyzed in the laboratory to determine the diffusion of the chloride in the bridge decks. This study revealed that no sign of corrosion was detected for the ECR rebars that were taken at the uncracked bridge deck locations. In addition, no delamination or spalling was observed for the bridge decks where bars in the core samples, which were taken at the cracked bridge deck locations, exhibited signs of corrosion. The collected ECR rebars samples were rated according to the degree of the corrosion that was observed on each bar. These ratings were used to develop condition/age relationships that were utilized to estimate the functional service life of bridge decks that are reinforced with ECR bars.

7.14. Corrosion of Reinforcement in Relation to Presence of Defects at the Interface Between Steel and Concrete

Author(s): T. A. Söylev, R. François

Publication: Journal of Structural Engineering, Vol. 17, No. 4, pp 447-455

Publication Date: July 2005

Abstract: In this study, steel-concrete interface defects were analyzed in order to define their potential to induce corrosion. Various types of steel-concrete interface defects were classified into two main groups: macro defects and micro defects. Gaps formed beneath horizontal reinforcement as a result of bleeding and settlement of fresh concrete were analyzed for macro defects. Micro defects presented no signs that could be identified by visual inspection and resulted not only from controlled pull-out of the steel bar but also from bleeding and settlement (but without the production of macro defects as found with gap formation). Apart from interface defects, cover concrete porosity was defined as an intrinsic defect. The effect of these defects on reinforcement corrosion was investigated. Macro defects have a direct effect on corrosion, whereas micro defects have no significant effect on corrosion. Where the level of intrinsic defects was high, these had a greater effect on corrosion than interface macro defects. The behaviors of conventional and self-compacting concrete (SCC) were compared. SCC was found to have better interface quality.

7.15. Finite element analysis of corrosion-induced cracking, spalling and delamination of RC bridge decks

Author(s): K. Zhou, B. Martin-Pérez, Z. Lounis

Publication: NRCC-48147, pp. 187-196

Publication Date: July 2005

Abstract: The corrosion of reinforcing steel in reinforced concrete (RC) bridge decks due to the application of de-icing salts in winter has been recognized as one of the major causes of highway bridge deterioration in North America. Corrosion-induced damage is usually manifested by longitudinal cracking, spalling, and/or delamination of the concrete cover due to the expansion of corrosion products accumulating around the reinforcement. This damage leads to reduction or loss of serviceability, safety, and service life of RC bridge decks. This paper presents finite element analyses of the behaviour of the concrete bridge deck cover subjected to reinforcing steel corrosion. The prediction of the damage caused by corroding reinforcing bars is established by calculating the induced stresses in the surrounding concrete. The numerical model is used to conduct a parametric investigation of several design variables. It is found from the analyses that different failure mechanisms govern depending on the geometry and configuration of the reinforcing bars in the concrete cover of the bridge deck. Finally, the impact of concrete overlays

on the governing failure modes of cracking, spalling and/or delamination of the concrete cover is investigated by using the model.

7.16. Effect of Cement Type on the Corrosion of Reinforcing Steel Bars Exposed to Acidic Media Using Electrochemical Techniques

Author(s): K. Sakr

Publication: Cement and Concrete Research, Vol. 35, No. 9, pp. 1820-1826

Publication Date: September 2005

Abstract: The effect of different percentages of cement components (tricalcium aluminate C_3A) on the corrosion of embedded reinforcing steel bars was studied in presence of 5% NaCI or 5% $MgSO_4$ solutions. Different electrochemical techniques namely; half-cell potential measurement, impressed voltage method and impressed current method were used. The C_3A in cement reduced greatly the corrosion of steel bars embedded in concrete subjected to chloride or sulphate solutions. In chloride solution, as the percent of C_3A increased in cement from 2% to 10% the steel corrosion decreased proportionally. The rate of corrosion in 5% $MgSO_4$ solution was decreased as the percent of C_3A increased from 2% to 6%. From 6% to 10% the steel corrosion rate was rapidly accelerated. In general the presence of chloride and sulphate solutions in surrounding media reduced the destructive effect of sulphate ions on embedded steel bars.

7.17. Mechanical Model for Unbonded Seven-Wire Tendon with Symmetric Wire Breaks

Authors: MacDougall, C., Bartlett, M.

Publication: ASCE Journal of Engineering Mechanics, Volume 131, Issue 12, Pages 1239-1247.

Publication Date: December 2005

Abstract: A mechanical model for unbonded seven-wire tendons with broken wires that accounts for the effects of interwire friction and contact forces between the tendon and surrounding concrete is derived. The model is an essential tool for predicting the response, and reliability, of unbonded posttensioned concrete structures containing corroded tendons with broken wires. For the case where the broken wires are symmetrically arranged around the tendon cross section, the model predicts: (1) the strain variation with distance from the break in the broken and unbroken wires; (2) the affected length, where strains in the broken wires are less than those in the unbroken wires; and (3) the prestress force remaining after wire breaks occur. The affected length has practical significance because techniques used in practice to detect wire breaks will fail if performed outside the affected length. Experimental data obtained using a novel strongback beam confirm the response predicted by the model and indicate the coefficient of interwire friction is 0.164 for uncorroded tendons.

7.18. Finite Element Analysis of the Effects of Radial Expansion of Corroded Reinforcement

Author(s): Y.G. Du, A.H.C. Chan, L.A. Clark

Publication: Computers and Structures, Vol. 84, No. 13-14, pp. 917-929

Publication Date: May 2006

Abstract: A finite element (FE) model of the effects of corroding reinforcement on the surrounding concrete was validated against the results of simulated corrosion tests in which internal pressure was applied to holes cast in concrete. The model was then used to explore the effects of bar radial expansion, due to the formation of corrosion products, on the cracking of cover concrete. The predictions were compared with test results from reinforced concrete

accelerated corrosion specimens. The aim of the analytical investigation was to reveal the mechanism for the development of concrete cracking due to the corrosion of reinforcement. The three-dimensional physical specimens were idealised as two-dimensional analytical models under a plane strain assumption. Corrosion of reinforcement was modelled as either an internal pressure or a radial expansion to analyse the results of simulated and accelerated corrosion specimens, respectively. The FE analytical results indicate that the radial expansion of corroded reinforcement causes concrete cover to crack in four different stages: internal cracking, external cracking, penetration cracking and ultimate-cracking. It was also found that the FE analytical results could be used to explain qualitatively the experimentally determined relationship between amount of corrosion for concrete cracking and ratio of concrete cover to bar diameter, as well as that between reinforcement bond strength and amount of corrosion.

7.19. Analytical Model for Corrosion-Induced Crack Width in Reinforced Concrete Structures

Author(s): Chun-Qing Li, Robert E. Melchers, Jian-Jun Zheng

Publication: ACI Structural Journal, Vol. 103, No. 4, pp. 479-487

Publication Date: July 2006

Abstract: Crack width is a parameter of the most practical significance for the design and assessment of reinforced concrete structures. Practical experience and observations suggest that corrosion-affected reinforced concrete structures are more prone to cracking than other forms of structural deterioration. Moreover, concrete cracking incurs considerable costs of repairs and inconvenience to the public due to interruptions. This gives rise to the need for a thorough investigation to achieve cost-effectiveness in maintaining the serviceability of concrete structures. This study attempts to derive an analytical model for corrosion-induced crack width based on the concept of smeared cracks. A merit of the derived model is that it is directly related to critical factors that affect the corrosion-induced concrete cracking. After verifying the derived model, a parametric study was undertaken to quantify the effect of these factors on cracking development. It was found that corrosion rate, as represented by corrosion current density icorr , is the most important single factor that affects both the time to surface cracking and the growth of crack width. It is concluded that the model derived in this paper can predict corrosion-induced crack width with reasonable accuracy.

7.20. Electro-chemical Chloride Extraction: Influence of C3A of the Cement on Treatment Efficiency

Authors: J.C. Orellan Herrera, G. Escadeillas, G. Arliguie

Publication: Cement and Concrete Research, Volume 36, Issue 10, , Pages 1939-1946.

Publication Date: October 2006

Abstract: The aim of this study was to clarify whether the C3A content of cement had a significant effect on electrochemical chloride extraction (ECE) treatment efficiency. It is known that a higher C3A content in a cement gives it superior chloride complexing ability resulting in the formation of an “insoluble” calcium chloro aluminate compound.

ECE was applied using cylindrical specimens made from concrete containing two levels of C3A (4.3% and 9.05%). Specimens were 5 cm in diameter and 10 cm in height. Steel was placed in the axial direction with an embedded length of 7 cm. These specimens were immersed in an NaCl solution and dried in a stream of air at 40 °C for 10 months. The corrosion was monitored

by half-cell potential and polarization resistance measurements. After steel depassivation, ECE was applied for 20, 30, 40 and 50 days using a constant current density of 1 A/m2 of steel. At the end of the treatment, the specimens were maintained at 20 °C and 70% RH in order to observe the evolution of the steel (electrochemical measurements).

The results show that, after 30 days of treatment, the chloride content remained constant in the specimen. This was probably due to OH− ion formation on the steel. The OH− ions "contribute" to the current transport, decreasing the ECE efficiency. Concerning the C3A content, ECE efficiency was slightly affected by C3A because only a part of the bound chloride ions was released. From the point of view of corrosion, half-cell potential showed a shift in the positive direction, indicating little corrosion activity at 20 °C and 70% RH. However, polarization resistance measurements showed that 2 months post treatment corrosion rates were significant, although the corrosion rate decreased from 6 μA/cm2 to 2.5 μA/cm2.

7.21. Mechanical Model for Unbonded Seven-Wire Tendon with Single Broken Wire

Authors: MacDougall, C., Bartlett, M.

Publication: ASCE Journal of Engineering Mechanics, Volume 132, Issue 12, Pages 1345-1353.

Publication Date: December 2006

Abstract: This paper presents the derivation and experimental validation of a mechanical model for unbonded seven-wire prestressing tendons with a single broken outer wire. The model has practical significance because corrosion of these tendons typically causes a single outer wire to fail first. The tendency for the tendon to deflect toward the broken wire causes strains in the unbroken wires to be unequal at any cross section. As a result, the strains in the two wires adjacent to the broken wire increase significantly due to the wire break. Equations are presented for: (1) the strains along the lengths of the broken and unbroken wires; (2) the affected length, where the broken wire can be detected because its strain is less than the strains in the unbroken wires; and (3) the prestress force remaining after the break occurs. Experimental data obtained from tests of seven-wire tendons performed on an 18.3 m (60 ft) long strongback beam validate the model.

7.22. Corrosion Inhibiting Systems for Concrete Bridges – 10 Years of Field Performance Evaluation (NRCC-49207)

Authors: Cusson, D.; Qian, S.

Publication: Fifth International Conference on Concrete under Severe Conditions Environment and Loading (CONSEC'07), Tours, France, June 4-6, 2007, pp. 1-10

Publication Date: June 2007

Abstract: The performance of nine corrosion-inhibiting systems for reinforced concrete structures exposed to the severe Canadian climate was assessed in the field on bridge barrier walls. These systems were composed of one or more of the following components: concrete admixtures, reinforcing steel coatings, and/or concrete surface coatings/sealers. The field evaluation consisted of annual corrosion surveys of half-cell potential and corrosion rate, as well as laboratory testing on concrete cores. After ten years, the main reinforcement at a depth of 75 mm was found in relatively good condition. Special bars embedded at a depth of 13-mm showed signs of advanced corrosion for all systems. Non-destructive corrosion evaluation of 25-mm deep special bars indicated lower risks of corrosion for corrosion-inhibiting systems composed of concrete admixtures.

7.23. Corrosion Process and Structural Performance of a 17 Year Old Reinforced Concrete Beam Stored in Chloride Environment

Authors: Vidal, T., Castel, A., François, R.

Publication: Cement and Concrete Research Volume 37, Pages 1551-1561.

Publication Date: August 2007

Abstract: The long-term corrosion process of reinforced concrete beams is studied in this paper. The reinforced concrete elements were stored in a chloride environment for 17years under service loading in order to be representative of real structural conditions. At different stages, cracking maps were drawn, total chloride contents were measured and mechanical tests were performed. Results show that the bending cracks and their width do not influence significantly the service life of the structure. The chloride threshold at the reinforcement depth, used by standards as a single parameter to predict the end of the initiation period, is a necessary but not a sufficient parameter to define service life. The steel–concrete interface condition is also a determinant parameter. The bleeding of concrete is an important cause of interface de-bonding which leads to an early corrosion propagation of the reinforcements. The structural performance under service load (i.e.: stiffness in flexure) is mostly affected by the corrosion of the tension reinforcement (steel cross-section and the steel–concrete bond reduction). Limit-state service life design based on structural performance reduction in terms of serviceability shows that the propagation period of the corrosion process is an important part of the reinforced concrete service life.

7.24. Temporary Corrosion Protection and Bond of Prestressing Steel

Authors: Marti, P., Ullner, R., Faller, M., Czaderski, C., Motavalli, M.

Publication: ACI Structural Journal, Volume 105, Number 1

Date of Publication: January February 2008

Abstract: The results of laboratory and field tests to investigate the performance of different temporary corrosion protection methods for prestressing steel are presented. It is demonstrated that a particular emulsifiable oil product applied to the prestressing steel showed by far the best corrosion protection behavior. Using this product, a pullout test with a long embedment length was performed on a post-tensioned seven-strand tendon with a plastic duct and compared with a reference test using untreated strands. Compared with the untreated strands, a bond shear stress reduction by a factor of approximately 2.5 was observed. It is shown that, generally, this reduction does not significantly influence the load-deformation response of posttensioned concrete members and that the emulsifiable oil does not need to be removed before grouting of the tendons.

7.25. Corrosion-Inhibiting Systems for Durable Concrete Bridges. I: Five-Year Field Performance Evaluation

Authors: Cusson, D., Qian, S., Chagnon, N., and Baldock, B.

Publication: ASCE Journal of Materials in Civil Engineering, Volume 20, Number 1, Pages 20-28

Date of Publication: January 2008

Abstract: The performance of nine commercially available corrosion-inhibiting systems for use in reinforced concrete structures exposed to corrosive environments was assessed in the field on

bridge barrier walls and in accelerated electrochemical cells in the laboratory. The corrosion-inhibiting systems included concrete admixtures, reinforcing steel coatings, and/or concrete surface coatings/sealers. The results of this study are presented in two companion papers, in which the field evaluation and laboratory investigation are reported. The field evaluation consisted of annual corrosion surveys of half-cell potential and corrosion rate, as well as remote monitoring with embedded instrumentation for the measurement of the environmental conditions. After five years of investigation, the system containing an inorganic-based admixture performed better than others in reducing the risk of reinforcement corrosion in the barrier wall. It was also found that the system using epoxy-coated reinforcement showed good early performance during the first year, but after, the risk of corrosion increased relatively faster than in other systems, possibly due to localized pitting corrosion developing in small defects or pores of the epoxy coating.

7.26. Corrosion-Inhibiting Systems for Durable Concrete Bridges. II: Accelerated Laboratory Investigation

Authors: Qian, S., Cusson, D., Chagnon, N., and Baldock, B.

Publication: ASCE Journal of Materials in Civil Engineering, Volume 20, Number 1, Pages 29-36

Abstract: Nine commercially available corrosion-inhibiting systems for use in concrete structures exposed to corrosive environments were evaluated on bridge barrier walls and in electrochemical cells. The results of this study are presented in two companion papers reporting on a five-year field evaluation and an accelerated laboratory investigation. The latter, presented in this paper, included the assessment of the effect of the corrosion inhibitors on the oxidation and reduction reactions by the cyclic voltammetry method, and their effectiveness in delaying or reducing corrosion by measurements of chloride thresholds and corrosion rates. The results indicated that the inorganic admixture and some organic admixtures performed very well in the saturated calcium hydroxide solution (pH of 12.6); however, their performance improvement over the control was not observed in a simulated concrete pore solution (pH of 13.5). Although tests in simulated concrete pore solutions cannot adequately simulate all the complex conditions usually found in the field, they were very useful to rapidly identify the effects of the corrosion inhibitors on the corrosion reactions, and to provide supporting information to the corresponding field evaluation.

7.27. Prediction of Reinforcement Corrosion in Concrete and Its Effects on Concrete Cracking and Strength Reduction

Authors: Li, Q.C., Yang, Y., Melchers, R. E.

Publication: ACI Materials Journal, V. 105, No. 1, Pages 3-10.

Date of Publication: January-February 2008.

Abstract: Based on extensive research on reinforcing steel corrosion in concrete in the past decades, it is now possible to estimate the effect of the progression of reinforcement corrosion in concrete infrastructure on its structural performance. There are still areas of considerable uncertainty in the models and in the data available, however. This paper uses a recently developed model for reinforcement corrosion in concrete to improve the estimation process and to indicate the practical implications. In particular, stochastic models are used to estimate the time likely to elapse for each phase of the whole corrosion process: initiation, corrosion-induced concrete cracking, and structural strength reduction. It was found that, for practical flexural

structures subject to chloride attacks, corrosion initiation may start quite early in their service life. It was also found that, once the structure is considered to be unserviceable due to corrosion-induced cracking, there is considerable remaining service life before the structure can be considered to have become unsafe. The procedure proposed in the paper has the potential to serve as a rational tool for practitioners, operators, and asset managers to make decisions about the optimal timing of repairs, strengthening, and/or rehabilitation of corrosion-affected concrete infrastructure. Timely intervention has the potential to prolong the service life of infrastructure.

8. Publications Related to Chloride and Corrosion

This chapter lists the references directly related to chlorides and corrosion of steel in concrete. Included are testing methods for assessing the threshold for corrosion, the rate of chloride intrusion, and the process of corrosion due to chlorides.

8.1. An Assessment of Four Methods of Determining the Free Chloride Content of Concrete

Authors: Arya, C., Newman, J. B.

Publication Materials and Structures Volume 23, pp. 319-330

Publication Date: 1990

Abstract; Four methods of determining the free chloride content of concrete are described and assessed in terms of reliability and practicability : (i) the direct use of a pore press to express pore fluid from mature concrete samples; (ii) leaching techniques, which are based on mixing powdered samples with a solvent and measuring the amount of chloride passing into solution; (iii) a method involving the measurement of total chloride by conventional techniques and subtracting the bound chloride measured using quantitative X-ray diffraction analysis; and (iv) via the measurement of total chloride using empirical relationships between free and total chloride derived from pore press tests.

8.2. Factors Affecting the Corrosion Rate of Steel in Carbonated Mortars

Authors: G. K. Glass, C. L. Page, N. R. Short

Publication: Corrosion Science Volume 32, Issue 12, Pages 1283-1294.

Publication Date: 1991 (PDF Unavailable)

Abstract: The corrosion of steel in carbonated mortar has been investigated by monitoring polarization resistance, corrosion potential and mortar resistivity. The results suggest that factors such as relative humidity and chloride contamination affect the corrosion rate via their influence on mortar resistivity. To account for the observed electrochemical relationships, most notably the linear correlation between corrosion rate and conductivity, and the exponential increase in corrosion rate with fall in corrosion potential, it is proposed that the corrosion kinetics of steel in carbonated mortar are subject to anodic control with the anodic reaction rate being limited by the resistance of the mortar. In this model, termed anodic resistance control, resistivity is viewed as a factor which may limit a half reaction rate in a similar way to diffusion and activation polarization. It is also shown that, when such a model is operating, the use of polarization resistance to monitor corrosion rate changes may still be justified provided the cathodic reaction rate is an exponential function of potential.

8.3. Factors Affecting Threshold Chloride for Reinforcement Corrosion in Concrete

Author(s): S. E. Hussain, Rasheeduzzafar, A. Al-Musallam

Publication: Cement and Concrete Research, Vol. 25, No. 7, pp. 1543-1555

Publication Date: October 1995

Abstract: Three cements with variable C3A contents were mixed with different levels of chloride, alkali and sulfate contents to study the effect of these parameters on pore solution composition. Effect of exposure temperature was also studied by curing the chloride-treated specimens at200 and 70°C. Pore solution was extracted using a high pressure pore solution extrusion device and analyzed for chloride and hydroxyl ion concentrations. Threshold chloride

for onset of reinforcement corrosion was computed using threshold [Cl-/OH-] ratio of 0.3. The results showed that C3A content and exposure temperature have very strong influence on threshold chloride content. Alkali content of cement has marginal effect whereas presence of sulfates along with chlorides has moderate effect on the threshold chloride content.

8.4. The Prediction of Corrosion Rates of Reinforcing Steels in Concrete

Author(s): H. Yalqyn and M. Ergun

Publication: Cement and Concrete Research, Vol. 26, No. 10, pp. 1593-1599

Publication Date: October 1996

Abstract: The effect of chloride and acetate ions on corrosion of steel in concrete was studied. The reinforcement corrosion was evaluated by measuring the corrosion potentials and corrosion current density using linear polarization resistance technique. The initial corrosion rates (i_o) of reinforcing steel in concrete containing either chloride or acetate ion were found to be higher as compared to concrete without admixture. The corrosion rate is very high at early days and decreases by time. The corrosion rate vs time curves for reinforcements in all three types of concrete blocks follow the same pattern. The following exponential quantitative relation between the corrosion rate (i_{cor}) and time (Θ) was proposed: $i_{cor} = i_0 \exp(-C\Theta)$ where C was termed as concrete corrosion constant having a value of 1.1×10^{-3} day^{-1} for the types of concrete samples under consideration.

8.5. Chloride Threshold for Corrosion of Reinforcement in Concrete

Author(s): Syed Ehtesham Hussain, Ahmad S. Al-Gahtani, Rasheeduzzafar

Publication: Materials Journal, Vol. 93, No. 6, pp. 534-538

Publication Date: November 1996

Abstract: Cement mortar specimens made with three different C3A cements with a steel bar embedded centrally were partially immersed in a 5 percent NaCl solution, and half-cell potentials were monitored. When the potential value reached -270 mV versus saturated calomel electrode (SCE), taken as the threshold potential for the onset of corrosion of the embedded bar, the specimens were taken out and pore solution extracted from the mortar surrounding the bar. The pore solutions were analyzed for Cl- and OH- concentrations and threshold Cl-/OH- ratios computed. The threshold Cl-/OH ratio seemed to depend on the pore solution pH and was found to vary from 1.28 to 2.0 for a pore solution pH of 13.26 to 13.36. The free (water-soluble)chloride concentration in the pore solution was converted into threshold free chloride and total (acid-soluble) chloride contents. It was found that the threshold free chloride content was 0.22 to 0.29 percent by weight of cement and was independent of the C3A content of the cement. However, the threshold total chloride content was found to depend on the C3A content of the cement and varied from 0.48 to 0.59, 0.73 to 0.85, and 1.01 to 1.20 percent for 2.43, 7.59, and 14 percent C3A cements, respectively.

8.6. Testing the Chloride Penetration Resistance of Concrete: A Literature Review

Author(s): K.D. Stanish, R.D. Hooton and M.D.A. Thomas

Publication: Report FHWA Contract DTFH61-97-R-00022 - “Prediction of Chloride Penetration in Concrete” (http://www.tfhrc.gov/hnr20/pubs/chlconcrete.pdf)

Publication Date: 1997

Abstract: In this document, a review of the current common methods for determining chloride penetrability of concrete is presented. First, some theoretical background of what influences the penetration of chlorides into concrete is presented in Section 3. The different mechanisms of chloride penetration are presented, followed by a further elaboration of the chloride diffusion theory. The influence of basic properties of concrete on its chloride penetrability is also discussed. In Section 4, individual test procedures are presented. First, the existing long-term procedures are discussed, namely the salt ponding (AASHTO T259) test and the Nordtest (NTBuild 443) bulk diffusion test. The existing short term tests are then presented. For each test, the procedure, the theoretical basis, and any advantages and disadvantages are presented. Also included in this document as an appendix is a glossary of some of the common terms related to chloride ingress testing and measurement.

8.7. The Presentation of the Chloride Threshold Level for Corrosion of Steel in Concrete

Authors: G. K. Glass, N. R. Buenfeld

Publication: Corrosion ScienceVolume 39, Issue 5, , , Pages 1001-1013.

Publication Date: May 1997

Abstract: It has been argued that presenting the chloride threshold level as a free chloride content or chloride to hydroxyl concentration ratio in the pore solution of concrete is an improvement over the more commonly used total chloride content. In this review the basis for this hypothesis is examined. Contrary to expectations, an analysis of the literature suggests that, on balance, bound chloride presents a corrosion risk, an effect which may be due to its contribution to the reservoir of available chloride at the steel concrete interface. Furthermore, the soluble hydroxyl concentration in the pore solution, which is largely determined by the presence of alkali metals, is not an adequate measure of the inhibitive properties of the cement. Its most important property appears to be its ability to resist a fall in pH to values below that required to sustain a passive film. Thus, in terms of currently used representations, chloride threshold levels are best presented as total chloride contents expressed relative to the weight of cement. This may be viewed as the total potential aggressive ion content expressed relative to the total potential inhibitor content. It may be possible to improve this by, for example, expressing the total chloride content relative to the alkaline reserves of the concrete, but further work is needed to confirm this hypothesis.

8.8. Modeling the Dynamic Corrosion Process in Chloride Contaminated Concrete Structures

Author(s): T. Liu, R. W. Weyers

Publication: Cement and Concrete Research, Vol. 28, No. 3, pp. 365-379

Publication Date: March 1998

Abstract: Corrosion of steel in concrete under service conditions is a process strongly influenced by the dynamics of environmental exposure. A total of 44 simulated bridge deck slabs were cast, and corrosion parameters were measured over a 5-year period. The monitored parameters included corrosion rate (linear polarization technique with and without a guard ring) and the concrete ohmic resistance and temperature. A series of 7 corrosion rates were established by admixing increasing amounts of sodium chloride. A non-linear regression model was developed, which demonstrates that corrosion of steel in concrete in service exposure conditions is a function of the concrete chloride content, temperature and ohmic resistance, and active corrosion time. Corrosion weight loss measurements demonstrated that the average annual corrosion rate is better estimated by the unguarded linear polarization method rather than the guarded ring method.

8.9. Structural Reliability of Concrete Bridges Including Improved Chloride Induced Models

Author(s): Kim Anh T. Vu, Mark G. Stewart

Publication: Structural Safety, Vol. 22, No. 4, pp. 313-333

Publication Date: 2000

Abstract: A structural deterioration reliability (probabilistic) model has been used herein to calculate probabilities of structural failure. New reinforced concrete corrosion initiation, corrosion rate and time-variant load models are proposed. Three durability design specifications are considered in a lifetime reliability analysis of a RC slab bridge. Time-variant increases in loads are considered also. It was found that the application of de-icing salts causes significant long-term deterioration and reduction in structural safety for poor durability design specifications. A reduced cover or increased water-cement ratio increases failure probabilities. When compared to the case of "no deterioration", it was observed also that the probability of failure only marginally increased for good durability design specifications. The approaches described herein are relevant to other physical infrastructure also.

8.10. The Influence of Chloride Binding on the Chloride Induced Corrosion Risk in Reinforced Concrete

Authors: G. K. Glass, N. R. Buenfeld

Publication: Corrosion Science Volume 42, Issue 2, Pages 329-344.

Publication Date: February 2000

Abstract: Chloride binding by the cement in concrete may affect the rate of chloride ingress and chloride threshold level which in turn determine the time to chloride induced corrosion initiation. In this work, a theoretical assessment of the influence of binding when chloride ingress results from diffusion, is presented. While chloride binding reduces the free chloride content within the concrete, it may increase or decrease the total chloride content depending on the distance from the concrete surface. The total chloride content at the transition between these effects is independent of the period of diffusion and value of the diffusion coefficient. The time to corrosion initiation of embedded steel is dependent on the corrosion risk presented by bound chloride. Bound chloride may participate in corrosion initiation when the establishment of pH gradients are required to sustain passive film breakdown. This is the result of the effect on the pore solution chemistry of the pH dependent solubilities of solid phases containing bound chloride that are very similar to that of calcium hydroxide. In some circumstances, the time to corrosion initiation may be reduced by an increase in binding because of the possible corrosion risk presented by bound chloride.

8.11. Corrosion Inhibition in Concrete Arising From Its Acid Neutralisation Capacity

Authors: G. K. Glass, B. Reddy, N. R. Buenfeld,

Publication: Corrosion Science Volume 42, Issue 9, Pages 1587-1598.

Publication Date: September 2000

Abstract: It has been postulated that the most important inhibitive property of concrete affecting the level of chloride required to initiate corrosion is its ability to resist a local fall in pH that might otherwise sustain passive film breakdown at a developing pit. In this work a novel technique termed differential acid neutralisation analysis was used to characterise this property. It was noted that many solid phases in hydrated cement paste have pH dependent dissolution

characteristics that may strongly influence the pore solution chemistry during corrosion initiation. While the important contribution made by calcium hydroxide has been widely recognised, other reactive hydration products contribute more than 75% of the resistance to a pH reduction to a value of 10. The resistance to a pH reduction (acid neutralisation capacity) to a value between 10 and 11 correlates reasonably well with the available chloride threshold level data. The inhibitive nature of the concrete environment, characterised by its acid neutralisation capacity, depends on the cementitious binder, decreasing in the order OPC > SRPC > PFA [approximate] GGBS. Care is needed to minimise adverse effects occurring at transient pH values on the steady state data obtained in an acid neutralisation test. However the indications are that differential acid neutralisation analysis may prove to be very effective as an analytical technique.

8.12. The Participation of Bound Chloride in Passive Film Breakdown on Steel in Concrete

Authors: G. K. Glass, B. Reddy, N. R. Buenfeld,

Publication: Corrosion Science Volume 42, Issue 11, Pages 2013-2021.

Publication Date: November 2000

Abstract: It is well known that solid calcium hydroxide may act to inhibit chloride induced corrosion of steel in concrete. This hypothesis has been recently extended to include the inhibitive and aggressive nature of other solids that exhibit pH dependent dissolution behaviour. Concrete constituents that resist a local fall in pH may inhibit corrosion, while bound chloride released by such a fall may participate in corrosion initiation. In this work the pH dependent solubility of chloride in concrete is demonstrated. It is shown that most of the bound chloride is released as the result of the rapid dissolution of at least two hydrated phases in chloride contaminated OPC concrete. This occurs at pH values that are high (above 11.5) compared to that considered necessary to sustain local passive film breakdown at the site of a nucleating pit. Thus, in theory, the corrosion risk presented by bound chloride at the steel-concrete interface may be very similar to that presented by free chloride.

8.13. Round-Robin Test on Chloride Analysis in Concrete-Part I: Analysis of Total Chloride Content

Author(s): Castellote, M., Andrade, C.

Publication: Materials and Structures, Vol. 34, pp. 532-556

Publication Date: November 2001

Abstract: The present paper gives part of the results of a Round Robin Test on chloride analysis in concrete, carried out by the Technical Committee TC 178-TMC. In this RRT, the analysis of total chloride, free chloride and the colourimetric determination of the front of chlorides in concrete have been tested. This paper reports the results corresponding to total chloride content. Water soluble chloride and colourimetric front are reported respectively in Parts II and III of the paper. A total of 30 laboratories around the world have participated in this RRT, and a total determination of 64 different analyses on triplicate specimens have been carried out. The procedure for the analysis of total chloride has been divided into two steps: extraction and analysis, discriminating the reliability of the procedure followed in each of them. Two different methods of extraction of total chloride from the solid sample (A1 and A2) as well as six different forms of analysing the resulting liquids (C1 to C6) have been tested. It was also decided that other methods could also be used to the choice of each laboratory, as "other methods" (A3 and C7 for extraction and analysis respectively). (The complete recipes of these methods can be

found in Annex 1 of the paper.) The statistical treatment of the data has been carried out according to the International Standard ISO 5725-1981 (F) for the determination of the reliability of testing methods: "Determination of the repeatability and reproducibility by Round Robin tests". As a final result the methods of extraction and analysis recommended for total chlorides have been the following: C1-C1, A2-C4., A2-C7, A3-C4. and A3-C7.

8.14. Round-Robin Test on Chloride Analysis in Concrete-Part II: Analysis of Water Soluble Chloride Content

Author(s): Castellote, M., Andrade, C.

Publication: Materials and Structures, Vol. 34, pp. 589-598

Publication Date: December 2001

Abstract: In Part I of this paper, general trends in the realization of this Round Robin Test on chloride analysis in concrete (carried out as part of the work developed by the Technical Committee TC 178-TMC), as well as the results corresponding to total chlorides were given. The present paper reports the results corresponding to the extraction of water soluble chlorides. Results concerning the determination of the penetration front of chlorides by colourirnetric techniques will be given in Part III. A total of 30 different laboratories around the world have participated in this Round Robin Test. All of them have performed analyses of total chlorides, having performed 64 different determinations of total chlorides in triplicate specimens. Among them, 20 laboratories have analysed water soluble chlorides. The total number of different determination of free chlorides, in triplicate specimens, has been of 37. Concerning the colourimetric method, 7 laboratories have taken part in the determinations, being the total number of different determinations of the colourimetric front, of 10. Two different methods of extraction from the solid sample (B1 and B2) have been tested. It was also decided that other methods could also be used to the choice of each laboratory, as "other methods" (I33). (The complete recipes of these methods can be found in Annex 1. The statistical treatment of the data has been carried out according to the International Standard ISO 5725-1981 (F) for the determination of the reliability of testing methods: "Determination of the repeatability and reproducibility by Round Robin tests". Finally, it has been concluded that both methods, B1 and B2, are reliable enough to extract water soluble chlorides from concrete. However the method that each laboratory currently uses (other methods) is not recommendable.

8.15. A Method of Ranking the Aggressive Nature of Chloride Contaminated Concrete

Authors: G. Sergi, G. K. Glass,

Publication: Corrosion Science Volume 42, Issue 12, , Pages 2043-2049.

Publication Date: December 2000

Abstract: In this work, previously reported titration data obtained on cement pastes and concretes are analysed. It is postulated that the inhibitive nature of concretes may be quantified by titrating a ground suspension to the endpoint indicated by phenolphthalein while the aggressive chloride content may be determined from the soluble chloride at the endpoint of this titration. Thus, the aggressive nature of chloride contaminated concrete may be ranked using the ratio of the extracted chloride to acid neutralisation capacity. Not only is there a theoretical justification for this, but it is relatively simple to determine.

8.16. Chloride-Induced Corrosion of Reinforced Concrete Bridge Decks

Author(s): Mumtaz Kassir, Michel Ghosn

Publication: Cement and Concrete Research, Vol. 32, No. 1, pp. 139-143

Publication Date: January 2002

Abstract: A closed-form solution is developed to predict the corrosion initiation time of reinforced concrete bridge decks using measured time varying surface chloride accumulations. The data base for the surface chlorides are core measurements at a shallow depth below the surface of 15 bridge decks in the snow belt region. The data base was collected during the bridges' biennial inspections over a period of 15 years. Regression analysis is used to represent the surface chlorides by an exponential variation with time. The time predicted to initiate corrosion is computed for different values of the effective diffusion coefficient and the concrete cover thickness. The results are compared to the constant surface accumulation model commonly used in the literature. As expected, the corrosion initiation based on constant chloride accumulation at the surface is faster (in some case by up to 100%) than the initiation time calculated from actual chloride concentration data. Such results are useful for the realistic estimation of the service lives of bridge decks and for scheduling bridge deck maintenance and rehabilitation programs.

8.17. Analysis of Total Chloride Content in Concrete Recommendation

Author(s): RILEM Technical committee 178

Publication: Materials and Structures, Vol. 35, No. 253, pp. 583-585

Publication Date: November 2002

Abstract: The present recommendation is the result of a Round-Robin Test on chloride analysis in concrete, carried out by the Technical Committee TC 178-TMC. A total of 30 laboratories around the world have participated in this RRT and 64 different analyses on triplicate specimens for three different chloride contents have been carried out. The procedure for the analysis of total chloride has been divided in two steps: extraction and quantification, being able to discriminate the reliability of the procedure followed in each of them. Two different methods of extraction of total chloride from the solid sample as well as six different forms of analysing the resulting liquids have been tested. It was also decided that other methods could also be used to the choice of each laboratory. The complete recipes and results including the statistical analysis can be found in [1]. Other round-robin tests can be found in [2, 3], being presently one the largest ever performed.

8.18. Analysis of Water Soluble Chloride Content in Concrete Recommendation

Author(s): RILEM Technical committee

Publication: Materials and Structures, Vol. 35, No. 253, pp. 586-588

Publication Date: November 2002

Abstract: As chloride ions in concrete are partially bound with the solid phases, only the so-called free chlorides are a risk of reinforcement corrosion. However, there are experimental difficulties of an accurate measurement of either bound or free chlorides due to: a) their relation is not constant as it evolves with time and temperature; b) there are no reliable analytical methods of quantification of bound chlorides. For free chlorides, it is generally accepted that the squeezing of hardened pastes of concretes gives the best approximation to the chloride ionic concentration existing in capillary pores [1-5]. Due to the complexity of this technique, and to its difficulty to be applied to concrete samples, methods based on leaching have been tried [6, 7]. The present recommendation is the result of a Round Robin Test on chloride analysis in

concrete, carried out by the Technical Committee TC 178-TMC. A total of 20 laboratories around the world have participated in this part of the RRT, making a total of 37 determinations of free chlorides in triplicate specimens for three different chloride concentrations. Two different methods of extraction of water soluble chlorides from the solid sample [6] and [7] were tested, taking as the target values those obtained by squeezing the powdered samples by applying high pressure. It was also decided that other methods could also be used to the choice of each laboratory. The complete recipes and all the results including the statistical analysis can be found in [8]. As a final result, the two methods proposed were considered to be a suitable reference for extracting water soluble chlorides. However, provided that the method given in [6] is easier to perform, it has been considered to take it as the reference method for extraction of free chlorides, and is the only one described in the present recommendation.

8.19. Prediction of Chloride Ions Ingress in Uncracked and Cracked Concrete

Author(s): Mohamed Boulfiza, Koji Sakai, Nemkumar Banthia

Publication: Materials Journal, Vol. 100, No. 1, pp. 38-48

Publication Date: January 2003

Abstract: The ingress of chloride ions into concrete plays a crucial role in reinforcing bar corrosion and, hence, for the durability and life of a structure. The problem is more acute once cracking has occurred. This paper presents mathematical models and numerical simulations for water movement and chloride ions ingress by diffusion and advection in cracked and uncracked concrete under saturated or unsaturated conditions. It has been shown that water movement at a crack is very sensitive to its saturation level and chloride ions ingress is also significantly affected by the presence of cracks. Empirical equations for the determination of chloride ions diffusion coefficients have also been proposed for a wide range of w/c ratios based on a comprehensive database and sample design nomographs for concrete cover shown.

8.20. A Method for Measuring the Chloride Threshold Level Required to Initiate Reinforcement Corrosion in Concrete

Author(s): Nygaard, P. V., Geiker, M. R.

Publication: Materials and Structures, Vol. 38, pp. 489-494

Publication Date: May 2005

Abstract: Information on the chloride threshold level that is necessary to initiate corrosion of steel reinforcement in concrete is required for service life calculations and performance testing of concrete. This paper proposes a method for determining the chloride threshold level causing the corrosion of steel in concrete. The method takes into account the need for accelerated chloride ingress and limitation of possible corrosion of steel parts not intended to act as anode.

8.21. Potentiostatic Study of Reinforcing Steel in Chloride Contaminated Concrete Powder Solution Extracts

Author(s): Chetan Kapat, Bulu Pradhan, B. Bhattacharjee

Publication: Corrosion Science, Vol. 48, No. 7, pp. 1757-1769

Publication Date: July 2006

Abstract: This paper presents the findings of an experimental investigation of potentiostatic study on reinforcing steel in chloride contaminated concrete powder solution extracts. Various zones of corrosion for the steel reinforcement at various chloride levels have been identified. In addition

the chloride concentration and pH value of these solutions were also measured. The major test variables include steel type, w/c ratio, cement content, and admixed chloride content.

8.22. Round-Robin Test on Methods for Determining Chloride Transport Parameters in Concrete

Author(s): Castellote, M., Andrade, C.

Publication: Materials and Structures, Vol. 39, pp. 955-990

Publication Date: October 2006

Abstract: This paper presents the results of a Round-Robin Test on methods for determining chloride transport parameters in concrete, carried out by the Technical Committee TC 178-TMC: ‘‘Testing and Modelling Chloride Penetration in Concrete’’ in which 27 different laboratories around the world have participated, using 13 different methods, in triplicate specimens, for 4 different mixes of concrete cast with different binders. Four different groups of methods have been tested: Natural diffusion methods (D), Migration methods (M), Resistivity methods (R) And Colourimetric methods (C). The statistical treatment of the data has been carried out according to the International Standard ISO 5725-2:1994 for the determination of the accuracy (trueness and precision) of measurement methods and results. Part 2: Basic method for the determination of the repeatability and reproducibility of a standard measurement method. In order to make an evaluation of these methods, four indicators have been identified and within each of them, several sub-indicators have been assigned. According to this system of classification, the methods have been classified following each indicator (trueness, precision, relevance and convenience), and also globally, by assigning different factors of importance, F.I., to the different indicators.

8.23. Methods of Obtaining Pore Solution from Cement Pastes and Mortars for Chloride Analysis

Author(s):L.J. Buckley, M.A. Carter, M.A. Wilson, J.D. Scantlebury

Publication: Cement and Concrete Research, Vol. 37, No. 11, pp. 1544-1550

Publication Date: August 2007

Abstract: Two techniques for the recovery of pore solution from cement mortars are examined: pore solution expression and miscible displacement using a high pressure permeameter. In the former, the pore solution is expressed from the mortar by crushing; in the latter, it is eluted from the mortar over 30 min by miscible displacement with water. Experimental results are presented for a range of cement pastes and mortars into which known amounts of chloride ion have been incorporated by using sodium chloride solution as the mix water. The results show that both eluted and expressed solutions exhibit a decrease in chloride ion concentration as the cement matrix ages, with the elution method showing a greater sensitivity to mix composition. Both methods show a decrease in chloride concentration as the water: cement ratio of the mix is increased. Overall, the high pressure elution method is capable of recovering a significantly higher proportion of the incorporated chloride. The application of these techniques to pore solution analysis is discussed.

8.24. Chloride-Induced Corrosion in Insufficiently Grouted Post Tensioned Concrete Beams

Author(s): Ha Minh, Hiroshi Mutsuyoshi, Hirotsugu Taniguchi,

Publication: Journal of Structural Engineering, Vol. 20, No. 1, pp. 85-91

Publication Date: January 2008

Abstract: An experimental program was carried out to clarify the effect of chloride-induced corrosion on posttensioned concrete (PC) beams under different grout conditions using the electrically accelerated corrosion testing method. A series of accelerated corrosion tests were performed to evaluate the influence of insufficient grout condition on corrosion of sheath and prestressing tendon. The radial pressure surrounding the sheath during the corrosion process was also investigated. After a period of accelerated corrosion, the mechanical behavior of the deteriorated PC beams was clarified through loading tests. Prestressing tendon corrosion and its correlation with beam load-carrying capacity was also investigated. The results of the experiments demonstrate a significant influence of corrosion of sheath and prestressing tendon on load-carrying capacity of PC beams. The width of the corrosion crack in PC beams increases with grout filling level inside the sheath. The presence of water inside the sheath leads to increased rates of corrosion of the sheath and prestressing tendon, resulting in an earlier deterioration in the load-carrying capacity of PC beams.

9. Publications Related to Carbonation of Concrete

This chapter summarizes the effects of carbonation on concrete members.

9.1. Damage Caused By Carbonation of Reinforced Concrete

Author(s): L.J.Parrott

Publication: Materials and Structures, Vol. 23, No. 135, pp. 230-234

Publication Date: May 1990

Abstract: Damage that can result from the carbonation of concrete cover and subsequent corrosion of the reinforcement is outlined. The factors influencing carbonation and corrosion are briefly reviewed. Measurement methods for field and laboratory assessments of carbonation, corrosion and damage are described. These methods are linked to a simple classification system for carbonation-induced damage and recommendations for further action.

9.2. Nonlinear Coupling of Carbonation and Chloride Diffusion in Concrete

Author(s): W. Puatatsananon, V. E. Saouma

Publication: Journal of Materials in Civil Engineering, Vol. 17, No. 3, pp. 264-275

Publication Date: May 2005

Abstract: External reinforced concrete elements exposed to chloride and/or CO_2 will eventually have a lower pH, which in turn will depassivate the reinforcement and initiate corrosion, thus causing spalling. This paper seeks to address the complex multiphysics nature of concrete environmental damage, which is governed by coupled nonlinear partial differential equations. Heat, relative pore humidity, chloride, and carbonation are all implemented in a two-dimensional coupled nonlinear finite-difference code. Coupling between carbonation and chloride diffusion is explored in the context of both homogeneous and heterogeneous concrete models. Numerical simulations results are presented.

9.3. The Experimental Investigation of Concrete Carbonation Depth

Author(s): Cheng-Feng Chang, Jing-Wen Chen

Publication: Cement and Concrete Research, Vol. 36, No. 9, pp. 1760-1767

Publication Date: September 2006

Abstract: Phenolphthalein indicator has traditionally been used to determine the depth of carbonation in concrete. This investigation uses the thermalgravimetric analysis (TGA) method, which tests the concentration distribution of Ca(OH)2 and CaCO3, while the X-ray diffraction analysis (XRDA) tests the intensity distribution of Ca(OH)2 and CaCO3. The Fourier transformation infrared spectroscopy (FTIR) test method detects the presence of C–O in concrete samples as a basis for determining the presence of CaCO3. Concrete specimens were prepared and subjected to accelerated carbonation under conditions of 23 °C temperature, 70% RH and 20% concentration of CO2. The test results of TGA and XRDA indicate that there exists a sharp carbonation front. Three zones of carbonation were identified according to the degree of carbonation and pH in the pore solutions. The TGA, XRDA and FTIR results showed the depth of carbonation front is twice of that determined from phenolphthalein indicator.

9.4. Performance of a Penetrating Corrosion Inhibitor in Concrete Affected by Carbonation-Induced Corrosion

Author(s): R. Heiyantuduwa, M. G. Alexander, J. R. Mackechnie

Publication: Journal of Structural Engineering, Vol. 18, No. 6, pp. 842-850

Publication Date: November 2006

Abstract: The performance of an organic, penetrating corrosion inhibitor in reducing the rate of corrosion and delaying the onset of corrosion in carbonated concrete was investigated. Laboratory trials were undertaken on specimens treated with the corrosion inhibitor before and after accelerated carbonation. Corrosion monitoring was undertaken for 11 months measuring corrosion rate, rebar potential, and resistivity. Results indicate that the penetrating corrosion inhibitor is capable of reducing corrosion rates and delaying the onset of corrosion under carbonation conditions. The effectiveness of the inhibitor was also assessed on site structures exhibiting severe carbonation-induced corrosion. Corrosion monitoring on site was done for a period of nine months. Findings from site studies confirmed that surface application of the corrosion inhibitor significantly reduced the corrosion rate of reinforcement embedded in carbonated concrete when compared with untreated elements.

9.5. Accelerated Protocol for Measurement of Carbonation Through a Crack Surface

Author(s): Laura Sullivan-Green, William Hime, Charles Dowding

Publication: Cement and Concrete Research, Vol. 37, No. 6, pp. 916-923

Publication Date: June 2007

Abstract: This paper introduces a method for accelerating experiments to quantify gaseous carbonation of cementitious materials through a sheltered crack surface. To date the majority of measurements of carbonation have focused upon the determination of the carbonation reaction through an open material face with no restriction to gaseous exposure. Experiments to determine the extent of carbonation through a crack surface can verify the extent to which restrictions of gaseous exposure can alter rates of carbonation into the crack surface as well as the depth into the crack to which the reaction occurs. The paper demonstrates that with experimental data the accelerated protocol can produce differences in outcomes in time intervals that are short relative to those in which the reaction occurs naturally. The experiment conducted to demonstrate the viability of the accelerated protocol involved measuring differences in the penetration of carbonation into the crack surface that resulted from differences in crack width. A byproduct of this experiment was a measurement of the depth into the crack (from the material face) to which carbonation occurs. It is not the intent of the paper to develop a theory of rates of carbonation, but rather to demonstrate that statistical differences are obtainable with the accelerated protocol

9.6. Permeability Characteristics of Carbonated Concrete Considering Capillary Pore Structure

Author(s): Ha-Won Song, Seung-Jun Kwon

Publication: Cement and Concrete Research, Vol. 37, No. 6, pp. 909-915

Publication Date: June 2007

Abstract: During carbonation process, the calcium phases present in cement are attacked by CO_2 and converted into $CaCO_3$ and the permeability of concrete is changing due to the change in porosity. The rate of carbonation depends upon porosity and moisture content of the concrete.

Especially in underground reinforced concrete structures, the interior portion of concrete surface may be exposed to carbonation and the exterior portion of concrete surface exposed to wet soil or underground water. As carbonation proceeds from outer surface into internal portion of concrete, microstructure is also changed continuously from outer surface into internal portion of concrete. Even the deteriorations in the structures due to the carbonation have been reported more, research on permeability characteristics of concrete considering carbonation and micro-structural information is very scarce. In this study, the permeability coefficient in carbonated concrete is derived by applying a capillary pore structure formation model in carbonated cement mortar and assuming that aggregates do not affect carbonation process in early-aged concrete as a function of porosity. The permeability obtained from the micro-level modeling for carbonated concrete is verified with the results of accelerated carbonation test and water penetration test in cement mortar.

9.7. Measurement Methods of Carbonation Profiles in Concrete: Thermogravimetry, Chemical Analysis and Gammadensimetry

Author(s): Géraldine Villain, Mickaël Thiery, Gérard Platret

Publication: Cement and Concrete Research, Vol. 37, No. 8, 1182-1192

Publication Date: August 2007

Abstract: This paper deals with two experimental methods to determine carbonation profiles in concrete. Gammadensimetry is a non-destructive test method able to measure the total penetrated CO2 and to monitor the carbonation process during laboratory accelerated tests. The second method is thermogravimetric analysis (TGA) supplemented with chemical analysis (CA): as TGA is performed on a small mortar sample not representative of the whole tested concrete, CA is needed to proportion the sample cement content, the sand content and to correct the TGA results becoming thus representative of the concrete mix. Consequently, TGA-CA gives accurate quantitative profiles in carbonated cementitious materials. Results are reported for an ordinary Portland cement paste, and three concrete mixes, containing siliceous or calcareous aggregates. The CO2 mass loss due to carbonation occurs from 530 to 950 °C, which overlaps the temperature range of the calcareous aggregate dissociation. To solve the problem, the origin of CaCO3 is carefully analyzed. Calcium carbonate ensuing from C–S–H carbonation dissociates in a lower temperature range than the more stable one ensuing from portlandite carbonation and from limestone, which enables C–S–H carbonation to be distinguished from calcareous aggregates. Therefore, TGA-CA allows the CaCO3 ensuing from C–S–H carbonation to be measured and to calculate the portlandite degraded by carbonation. Thus, the total calcium carbonates profiles can be deduced even when calcareous aggregates is present in the concrete mix.

9.8. Effect of Carbonation on Concrete Bridge Service Life

Author(s): Lakshmy Parameswaran, Ram Kumar, G. K. Sahu

Publication: Journal of Structural Engineering, Vol. 13, No.1, pp. 75-82

Publication Date: January 2008

Abstract: An increase in the number of distressed bridges and the limited financial resources emphasize the need for an efficient bridge management system (BMS) for India. Assessment of the remaining life of bridges becomes an essential step in BMS, which involves modeling of complex deterioration mechanisms in concrete due to chemical attacks, such as carbonation, chloride, sulfate, and so on. Lack of information on material properties used in bridge

construction, construction techniques, exposure condition, and maintenance quality adopted make the remaining life assessment of bridges more complicated. Therefore, a parametric study has been carried out to understand the deterioration of concrete bridges due to carbonation. Effect of carbonation on the initiation and propagation time of corrosion was also included in the study. Based on the study, modifications are suggested in the clauses of Indian concrete bridge design standard IRC: 21 (2000) so as to enhance the service life of bridges.

10. Non-Destructive Evaluation Techniques

10.1. Nondestructive Techniques to Investigate Corrosion Status in Concrete Structures

Author(s): Nicholas J. Carino

Publication: Journal of Structural Engineering, Vol. 13, No. 3, pp. 96-106

Publication Date: August 1999

Abstract: A critical step in selecting the most appropriate repair strategy for a distressed concrete structure is to determine the corrosion status of reinforcing bars. Because of the complexity of the corrosion process, it is prudent to involve personnel who are experienced in the corrosion of steel in concrete. The corrosion engineer may employ a variety of tools to help make an assessment of the corrosion conditions. This paper provides an overview of the corrosion of steel in concrete and presents some nondestructive electrochemical tools that are commonly used in corrosion investigations. The objective is to provide the repair specialist with basic information to allow effective communication with the corrosion engineer. Electrochemical principles involved in the corrosion of steel in concrete are reviewed. Subsequently, the half-cell potential method, the concrete resistivity test, and the linear polarization method are discussed. The principles of operation and the inherent limitations of these methods are emphasized.

10.2. Corrosion Detection of Steel Cables using Time Domain Reflectometry

Author(s): Wei Liu, Robert G. Hunsperger, Michael J. Chajes

Publication: Journal of Structural Engineering, Vol. 14, No. 3, pp. 217-223

Publication Date: May 2002

Abstract: Corrosion of steel cables and reinforcing steel in concrete structures is a major cause of structural deterioration. The current methods for corrosion detection suffer from several significant drawbacks. In this paper, a nondestructive evaluation technique is developed that is capable of determining the location and severity of corrosion of embedded or encased steel rebar and cables. This technique utilizes time domain reflectometry (TDR), which has been traditionally used to detect electrical discontinuities in transmission lines. By installing a sensor wire alongside the steel reinforcement, the reinforcement can be modeled as an asymmetric, twin-conductor transmission line. Physical defects of the reinforcement, such as abrupt pitting corrosion, general surface corrosion, and grouting voids, will change the electromagnetic properties of the line. They can be modeled analytically, and identified using TDR. TDR measurement results from several fabricated bridge cable sections with built-in defects are reported. Based on the initial results, the TDR corrosion detection method has proven to be more robust than the existing methods, because it allows one to detect, locate, and identify the extent of corrosion damage.

10.3. Location of Prestressing Steel Fractures in Concrete

Author(s): H. Scheel, B. Hillemeier

Publication: Materials Journal, Vol. 15, No. 3, pp. 228-234

Publication Date: May 2003

Abstract: The remanent magnetism method allows the identification of potentially unsafe conditions in pretensioned and posttensioned concrete structures by locating fractures in the prestressing steel. This nondestructive method identifies fractures of single wires, even when

they are bundled with intact wires. The magnetic field of tendons is measured at the concrete surface, once they have been premagnetized with an electromagnet. Fractures produce characteristic magnetic leakage fields, which can be measured with appropriate sensors at the concrete surface. The parameters associated with fractured wires have been quantitatively identified in the laboratory and have been confirmed in the field. The knowledge of these parameters allows us to draw conclusions about the reduction of a cross-sectional area or the number of fractured wires in a tendon. The method has been successfully applied outside of the laboratory on full size bonded and unbonded posttensioned structures.

10.4. Pro's and Con's of Half-Cell Potentials and Corrosion Rate Measurements

Author(s): Thomas Frølund, Oskar Klinghoffer, Henrik E. Sørensen,

Publication: Structural Faults + Repairs, International Conference, London, U.K

Publication Date: July 1st-July 3rd 2003

Abstract: Half-cell potentials and corrosion rate measurements are compared and evaluated. The paper presents four different on-site cases. The first example is from a bridge pillar exposed to deicing salts. This example shows a good correlation between corrosion rate and half- cell potential mapping. The second is a dry structure where high half-cell potentials were measured and shown to be directly misleading, while the corrosion rate provided the reliable results. In the third testing case very low half-cell potentials were measured in a wet structure, and shown not to be a reliable indicator of the corrosion activity, again indicated accurately by the determination of corrosion rate. The last example is an underground parking with leaking water/ de-icing salts from the above street. In this case the half -cell potentials indicated high corrosion risk while the corrosion rate is rather low. In all cases the actual corrosion was documented by exposing the reinforcement during visual inspection.

10.5. Half-Cell Potential Measurements - Potential Mapping on Reinforced Concrete Structures

Authors: Elsener, B., with contributions from C. Andrade, J. Gulikers, R. Polder and M. Raupach

Publication: Materials and Structures, volume 36, pp. 461-471

Publication Date: September 2003

Abstract: This RILEM Technical Recommendation intends to provide the background, a description of the application and guidelines tbr the interpretation of half-cell potential measurements on reinforced concrete structures. It covers both: point measurements (mostly used during inspection, thus in the project phase of a restoration) and potential mapping.

11. Summary of Strand Corrosion Indicators

Corrosion of steel in concrete is caused by two electrochemical reactions: an anodic reaction, capable of producing electrons, and oxidizing iron, and a cathodic reaction, capable of consuming electrons [ACI 222R]. In general an appropriately made concrete is very alkaline (basic) exhibiting a high pH. As a result the electrochemical reaction typically results in the formation of iron oxides or hydroxides which form a protective layer around the steel. This protective layer is fairly stable if the concrete maintains a high pH and is not subjected to external attack by environmental or chemical products.

Inevitably the concrete mix may be poorly designed, the concrete member may be subjected to harsh environments, or the surfaces may be exposed to chemical attack. This results in a decrease in the pH, the loss of the protective layer, and corrosion of the reinforcement. Based on a literature review corrosion of prestressing strand in concrete bridge beams can be associated with many conditions. The most common conditions that affect bridge beams include:

- Chloride Attack
- Carbonation of the Concrete

A brief summary of each condition on the cause of corrosion is discussed in the following sections.

11.1. Chlorides

The most common cause of initiation of corrosion of steel in concrete is the presence of chloride ions. The source of chlorides may be attributed to admixtures, contaminants, marine environments, industrial brine, or deicing salts. The process by which chlorides initiate corrosion of steels is well described in ACI 222R. In brief, when chloride ions reach the steel the previously described protective layer is lost. The pH around the steel decreases, the chloride ions react with the ferrous ions and diffuse away from the steel. Once they reach an area of high pH iron hydroxide is formed and the chloride is released allowing it to migrate back to the steel. The process is repeated thus leading to continued oxidation of the iron and significant corrosion.

The process by which the steel loses its protective film is termed depassivation. This can occur locally due to the ingress of chlorides or over a large region due to acidification of the area around the steel as a result of chemical reactions with the carbon dioxide present in the atmosphere.

Chlorides may be present in the concrete, as result of the use of contaminated ingredients in the manufacture of the concrete mix, or as result of an external contamination prior to construction. This has become less of a problem in recent years as knowledge of the corrosion process is more widely understood.

Chlorides may also be transmitted to the concrete through exposure to water, marine environments, or to the use of de-icing salts (NaCl, $CaCl_2$ and $MgCl_2$) a necessary practice in cold climates. Leaking from construction joints also contributes to increase in surface chloride concentration. The presence of waterborne chlorides results in a saturation of the concrete pores with an acidic solution. This leads to a decrease in the alkalinity of the concrete and the propagation of oxidation of the steel.

The propensity and rate at which surface chlorides are transferred is directly related to the porosity of the concrete. The volume of the pore solution is directly proportional to the porosity

of the concrete. A greater porosity would lead to ingress of chloride ions at a higher rate. The concrete may become porous due to carbonation or it may be manufactured with significant porosity due to the use of low strength cement or inadequate curing. The quality of concrete and the thickness of concrete cover are of vital importance in providing protection to steel against initiation of corrosion.

Most reliability analyses have assumed that the corrosion rate is constant during the corrosion propagation period. However it is expected that the formation of rust products on the steel surface will reduce the diffusion of the iron ions away from the steel surface. Also the area ratio between the anode and cathode is reduced. This suggests that the corrosion rate will reduce with time namely, rapidly during the first few years after the initiation but then more slowly as it approaches a nearly uniform level.

11.1.1. **Chloride Measurement Techniques**

There are a variety of methods established for measuring the level of chlorides within the concrete. Chlorides are present in concrete as both free chlorides in the pore solution and as bound chlorides within the cement paste products. It is often assumed that the main contribution to corrosion is in the form of the free chlorides present in the pore solution. Research by G.K. Glass et. al. in 2000 (Section 8.12.) has shown that the bound chloride is rapidly released as the pH decreases in the pore solution. Based on the results of his research the *total* chloride content is recommended as an indicator for determining the potential for corrosion.

The two common methods of measuring the total chloride measurement in the United States are defined in ASTM C1152 Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete and AASHTO T-260 Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials. The methods measure the total soluble chloride in the concrete by pulverizing a 10g sample such that it is able to pass through a fine sieve (No.20 sieve for ASTM, No.50 sieve for AASHTO). Both methods allow the use of potentiometric titration to determine the chloride content. The AASHTO method provides an additional approach using Atomic Absorption (procedure B). The chloride content is measured and reported as either a percent chloride by mass of cement or by mass of concrete. The amount can also be quantified as pounds of chloride per cubic yard of concrete. Assuming an air dry density of normal weigh concrete of 3815lb/yd^3 and cement content of 658lbs per cubic yard, the weight of chloride can be found directly from the percentages.

Other methods exist for measuring the chloride content of concrete. These include rapid methods such as the one developed by the Strategic Highway Research Program SHRP-S-328. New methods have also been recommended to increase the repeatability and reproducibility of determination of chloride content. RILEM Technical Committee TC 178-TMC conducted a round robin test series involving 30 laboratories from around the world conducting over 64 analyses in triplicate. The result of the study was that determination of chloride content can be repeatable and reproducible. Based on the investigation a new method was recommended and is outlined in reference 8.17. The method is similar in concept to the ASTM and AASHTO methodologies however it varies enough that it would likely produce more accurate results. Nevertheless due to the standardization of the AASHTO method in the U.S., it is the recommended method for use by PennDOT.

11.1.2. **Chloride Threshold Levels**

Corrosion is thought to be a concern if the total acid soluble chloride is above a threshold value. As noted in ACI 222R two threshold ranges are commonly used. They are defined below with respect to chloride percent by mass of cement, percent by mass of concrete, and lbs of chloride per cubic yard of concrete. The conversions between the values are made assuming an air dry density of normal weigh concrete of 3815lb/yd^3 and cement content of 658lbs per cubic yard.

Comite Euro-International du Beton (CEB) Threshold:

- 0.40% Cl^- by mass of cement
- 2.4 lbs of Cl^- per cubic yard concrete
- 0.06% Cl^- by mass of concrete

United States Threshold:

- 0.15% to 0.23% Cl^- by mass of cement
- 1.0 to 1.5 lbs of Cl^- per cubic yard of concrete
- Approximately 0.026% to 0.040% Cl by mass of concrete

Though ACI222R provides general recommendations on chloride threshold levels many conflicting studies exist on the appropriate value to use. A review by Glass and Bunefield in 1997 indicated that research studies have shown that the threshold value can vary from 0.17% to 2.50% Cl^- by mass of cement. This range was based on a considerable number of variables in both the concrete and the methods used to generate corrosion.

While most prestressed concrete bridge beams are manufactured in a fairly consistent manner the constituents used in the concrete mix vary based on the era in which they were built. This is exemplified by the addition of plasticizers in the 1970s and today with viscosity modifying admixtures. As a baseline a value of 0.032% by mass of concrete is recommended in accordance with the research conducted by the ATLSS Center [reference 6.7.]. This threshold value will be further validated through destructive testing of concrete samples from the beams recovered from over 30 years of service in PA.

11.1.3. **Chloride Penetration Resistance Determination**

In new concrete members or existing members that have not shown corrosion damage it may be important to assess the risk for chloride intrusion. Three test methods are commonly identified for determining the penetration resistance of concrete to chloride intrusion:

- AASHTO T259-02: Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration
- AASHTO T277-05: Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
- ASTM C 1202 - 07: Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration

The most widely accepted method is AASHTO T-259. This test involves ponding a 3% solution of sodium chloride over a concrete sample for 90 days, allowing it to dry out then destructively

determining the acid soluble chloride at various depths from the surface. Though this test accurately determines the propensity for chloride intrusion the test is costly and time consuming.

AASHTO T277 and ASTM C1202 provide rapid methods of assessing the chloride levels. These techniques involve measuring the amount of electrical current which passes through a 2in sample over a 6 hour period. While these methods provide a rapid measurement the results are sensitive to the type of concrete constituents used. Certain admixtures may allow much higher currents to pass through the sample giving a false indication of low penetration resistance. To properly correlate the information generated from the rapid tests with chloride penetration resistance a supporting ponding test should be conducted.

11.1.4. **Chloride Removal Techniques**

Techniques have been developed to remove chlorides from contaminated concrete members. This work has been largely conducted on slabs however the process can be extended to bridge beams as well. The process is known as Electrochemical Chloride Extraction or ECE. It involves passing a current between an external anode and the reinforcing steel. This causes the Chloride ions to move away from the steel to the external anode. The methodology is briefly discussed in reference 7.20.

11.1.5. **Rate of Corrosion with the Presence of Chlorides**

The corrosion rates of reinforcing steel in concrete depend on various factors. The most important ones, are moisture content of concrete, access to oxygen (permeability of concrete), and especially the presence of chloride ions in concrete. The corrosion rate increases with the increase in the chloride levels in the concrete. This is a result of an increase in conductivity of concrete as the chloride ions increase, and the chloride ions can also complex with ferrous ions to form a water soluble product that can accelerate corrosion rate. Corrosion rates decrease exponentially with time most probably due to the lack of electrolyte.

Researchers have developed a number of models which can be used to assess the diffusion of chlorides into concrete and the corresponding occurrence of corrosion. From these models the remaining service life of various members can be determined. The numerical background is well discussed in reference 3.1.

11.2. Carbonation

Carbonation of concrete is the process by which atmospheric carbon dioxide CO_2 diffuses into the surface pores of concrete and decreases the pH of the pore solution. This front of decreased pH penetrates the concrete and results in the loss of the steel the protective layer allowing for the initiation of corrosion. Though carbonation is attributed to CO_2 gas, the reaction occurs in the pore solution. Thus carbonation is most likely to occur in concrete members subject to dry-wet cycles. In addition the presence of cracks and high porosity can accelerate the propagation of the carbonation front. Unlike chloride intrusion, carbonation of the concrete typically forms over the entire face of the member. As a result complete carbonation can result in large scale corrosion of large areas of the member at the same time.

For carbonation to occur the environment must have very high levels of carbon dioxide. The atmospheric concentration of carbon dioxide typically ranges from 0.02% to 0.06% in urban areas. At these levels carbonation is unlikely to occur. Levels may be elevated in particular regions such as industrial areas. Carbon dioxide from vehicle emissions is a possible cause of

carbonation of bridge beams. The concentration would need to be very high however since carbon dioxide is heavier than oxygen and would likely decrease above the roadway.

11.2.1. **Causes of Carbonation in Concrete Systems**

Parrott (9.1.) gave various reasons for carbonation to occur in concrete members which are stated below

- Compressive Strength of Concrete: Rate of carbonation depends on the compressive strength of the concrete. For example concrete with higher compressive strength has a higher resistance to carbonation than a lower compressive strength concrete.
- Water / Cement Ratio: The use of a low water cement ratio reduces the porosity of the concrete surface and restricts inward diffusion of carbon dioxide thus reducing the propensity for carbonation.
- Surface Moisture: The moisture condition of the concrete surface will also affect the rate of carbonation; at high moisture content the pores will be partially filled with water and restrict the ingress of carbon dioxide.
- Porosity: Inadequate early age curing of concrete can lead to rapid carbonation by causing a high porosity at the exposed surface
- pH of the Pore Solution: Corrosion of steel in concrete depends on the pH of the surrounding pore solutions. Carbonation is very sensitive to this pH. Corrosion initiates at a pH of about 11 in carbonated concrete but presence of chlorides can raise the threshold value.
- Relative Humidity: If the concrete around the steel remains dry (i.e. with an internal relative humidity below 70%) then the rate of corrosion will be negligible in the carbonated concrete. However the seasonal variations of climate will ensure that under external exposure conditions the relative humidity around the steel becomes high enough for corrosion during at least a part of each year.

11.2.1.1 Measurement of Carbonation Depth using Phenolphthalein

Carbon dioxide which penetrates the surface of concrete can react with alkaline components in the cement paste, mainly $Ca(OH)_2$ this is the carbonation of the concrete. This process leads to reduction of pH values of the pore solution to less than 9.0. The depth of carbonated concrete is called the depth of carbonation. The reduction of pH value can be made visible by the color change of a suitable indicator. A solution of 1% phenolphthalein in 70% ethyl alcohol is suitable for determining the depth of carbonation. Phenolphthalein turns non carbonated concrete red, and remains colorless in carbonated concrete. In order to measure the depth of carbonation in concrete specimens a slice is broken off thick enough to avoid any chance of carbon dioxide penetration from the end surface affecting the observed measurement from the side surfaces.

The indicator method does not make it possible, however, to determine whether the reduction of pH value may have resulted from influences other than the absorption of CO_2 (e.g. SO_2, HCl or other acidic gases). The color change observed after spraying with phenolphthalein may be due to reactions observed on the newly created surfaces therefore proper handling of the pieces must be maintained prior to testing.

11.3. Corrosion Measurement Methods

The presence of corrosion or prestressing steel can be identified by a number of well established non destructive techniques. These techniques have been used by DOTs and inspectors for a number of years and have ASTM recommendations to support them.

11.3.1. **Delamination Determination**

The majority of methods involve determination of delaminations. The methods which are used for this purpose include:

- ASTM C597 Standard Test Method for Pulse Velocity Through Concrete
- ASTM C1383 Standard Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method
- ASTM C4580 Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding
- ASTM D6087 Standard Test Method for Evaluating Asphalt-Covered Concrete Bridge Decks Using Ground Penetrating Radar

Based on field observations of beams in Pennsylvania corrosion damage can occur in the soffit, web, or top of the beam. The beams are often elevated and are not easily accessed. Furthermore, delamination is often associated with other forms of damage which are visually observable. Lastly, delamination of the tension zone, the underside of the beam, is not critical for strength determination. Thus assessment of delamination on the underside of the beam is not imperative. To examine this methodology the research program will examine the use of ASTM C4580 to determine delamination by sounding. If this indicates significant delamination then other methods may be used. GPR will be investigated if damage of the top flange is observed.

11.3.2. **Corrosion Potential Mapping**

An effective method for measuring the presence of active corrosion relies on the electrochemical process that occurs during corrosion. The method has been standardized as ASTM C876 Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete. This method has been developed and used extensively for concrete reinforced with conventional reinforcing bars. The procedure involves measuring the voltage differential between an external half cell electrode and the embedded steel. The half cell electrode is composed of a copper electrode in a copper sulfate solution (CSE), silver / silver chloride (SCE), or mercury / mercury chloride.

For conventional steel in concrete a voltage potential of less than -350mV (CSE) is a strong indicator of corrosion activity. This value is not definitive for prestressing steels, for large concrete covers, or for concretes with certain constituents. Consequently it is recommended that a map of the potential of the beam be developed and that corrosion activity be identified by identifying large relative changes in potential over the surface. It is important to note that for some prestressed concrete beam applications the steel may be isolated from each other. For these conditions it is important to ground the half cell to each respective strand being investigated. Due to the damage involved in achieving a ground this approach may not be feasible beams when the strands are electrically isolated.

11.4. Recommended Investigative Approach for PennDOT Study

To assess the methods recommended by ACI 222R and NCHRP 558 sections of decommissioned bridge beams will forensically examined. The following techniques will be employed. The final recommendations will be developed and submitted for review as part of the PennDOT research project.

- Cover measurement of all strands
- Potential mapping in accordance with ASTM C876
- Visual inspection including mapping and description of crack size and dimension, spalls, delaminations.
- Delamination investigation using a sounding rod in accordance with ASTM C4580
- Comparison of visual inspection, sounding, and potential mapping to identify regions for coring.
- Carbonation testing on cores and drilled holes using Phenothalene
- Acid Soluble Chloride determination from cores above corrosion spots AASHTO T259.
- Petrographic analysis of concrete
- Strength assessment of concrete

12. PennDOT- Non-Composite Adjacent Prestressed Concrete Box Beam Bridges Survey

In 2005, the fascia beam of Span 3 of an adjacent prestressed concrete box beam bridge that supports Route 1014 over I-70 collapsed. There was an extraordinary amount of damage to the fascia beam due to over-height vehicle collisions and long term corrosion of the prestressing strands. The damage to the beam was severe enough to result in failure under its own weight.

Due to this failure, PennDOT sent out a survey in 2006 to all fifty states and Ontario, Canada regarding this type of structure. The survey was created to obtain information about each state's experience with these bridges such as the number of bridges in the state, special inspections of these bridges, any and all closures /failures, and the factors that lead to these closures /failures. Twenty-three out of the fifty-one surveys were returned, six of which reported having a failure or closure. These six states were New York, Ohio, Florida, Indiana, Illinois, and Colorado.

12.1. New York Bridges

New York reported having four non-composite adjacent prestressed box girder bridges in the state system and 465 in the local system. They reported a bridge closure on the survey however follow-up with the DOT revealed that the bridge was only given a "yellow flag." Under a yellow flag the bridge is monitored closely for 1 year. The DOT noted that corrosion of strands has been observed and spalling and delamination has occurred with concrete falling on to travel lanes of Interstate below.

12.2. Ohio Bridges

Ohio department of transportation (ODOT) reported having 801 bridges of this type in the state system and 2,493 in the local system. They have only had one known failure in Cuyahoga County in Cleveland. The failure occurred in the fascia beam. Before the beam collapsed, the entire bottom had spalled off exposing all stands. Most of the strands were broken and hanging down to the water below. The strands that were not broken were drastically corroded. Six months before the beam collapsed, it was sagging as much as 6in. Images of the Cuyahoga County bridge before and after failure are illustrated in Figure 1.

ODOT conducts a condition rating of prestressed beams in accordance with the following rating definitions:

9 No noticeable or noteworthy deficiencies which affect the condition of the superstructure.

8 Minor problems noted. Minor deficiencies.

7 Minor cracking of beams spalling along edge.

6 Minor cracking. One or two strands exposed. Some joints between beams leaking with subsequent spalling.

5 Some beam end deterioration. 5 or 6 joints between beams leaking, spalling with 5 or 6 strands exposed. No broken strands.

4 Beam end deterioration. Many joints leaking. Spalling concrete. 10-20% strands exposed. 1 or 2 broken and hanging down.

3 25%- 50% strands exposed. 3-5 broken and hanging down.

2 Bridge critical. 50% - 60% of strands exposed. At least 5 strands were broken and hanging down.

1 Bridge closed. Many exposed strands. Several beams have noticeable sag.

0 Bridge closed. Nearly all strands are exposed. Many broken strands hanging down. Beams are sagging.

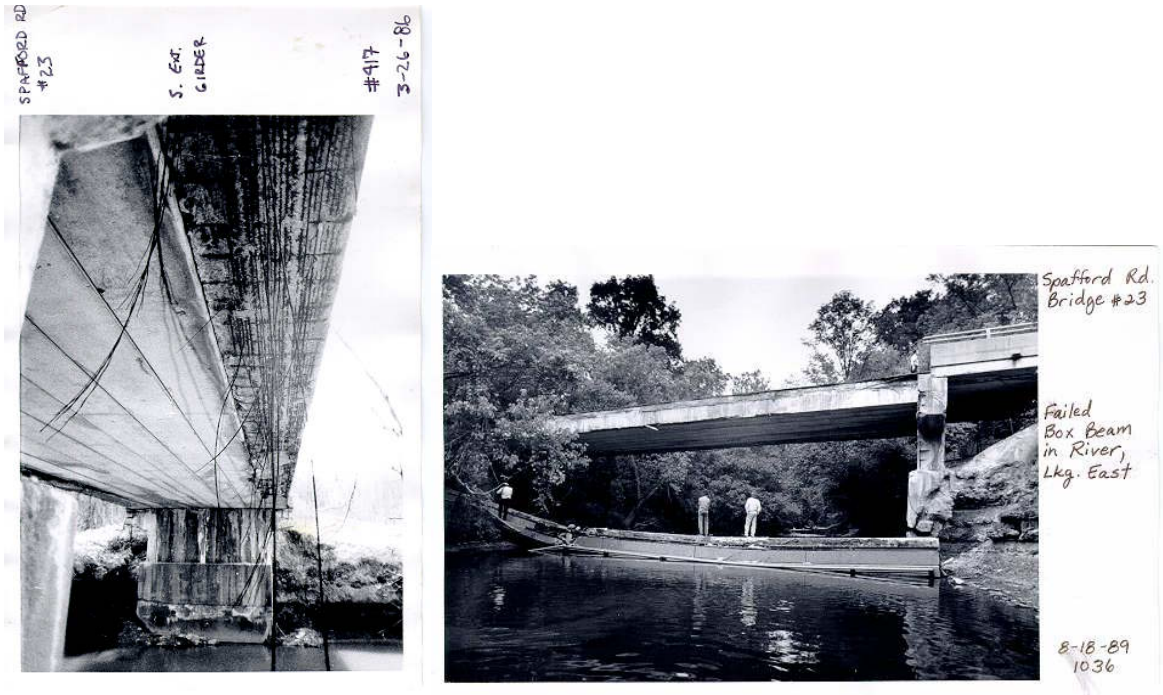

Figure 1: Cuyahoga County Bridge Failure

12.3. Florida Bridges

Florida had no record of having any non-composite adjacent prestressed concrete box beam bridges. However, they have prestressed Sonovoid flat slab bridges which exhibit similar problems. These bridges are fabricated from precast prestressed concrete planks containing sonotube void forms (Figure 2). The planks are grouted between units and laterally post-tensioned together as illustrated in Figure 3.

In their state system they have 328 of these structures and 1167 in their local system. Florida has reported having one closure in a local government bridge in South Florida. The bridge carried traffic over a canal that carried brackish water. The canal was used by jet skis which sprayed water on the underside of the structure. There was noted deterioration, spalling, and exposed prestressing strands in the inspection report. Due to the continuous water spray, with the prestressing strands exposed, corrosion was accelerated and resulted in broken strands. The bridge was closed as a result, and repairs were made.

Additional repairs are being made on these structures. Rehabilitation of three Sonovoid bridges was conducted by Bolton-Perez and Associates of Miami Florida in 2005. The repair consisted of replacing the transverse post-tensioning bars, grouting the transverse bars and joints between units, doweling hoops into the planks and adding a 5in composite concrete topping. The additional topping weight was accommodated by the additional strength provided by the composite action. Composite action was achieved by cleaning the surface of the beams and intentionally roughening them to ¼ - in. transverse to the span. A detail of the deck replacement is illustrated in Figure 4.

Figure 2: Sonovoid bridge deck

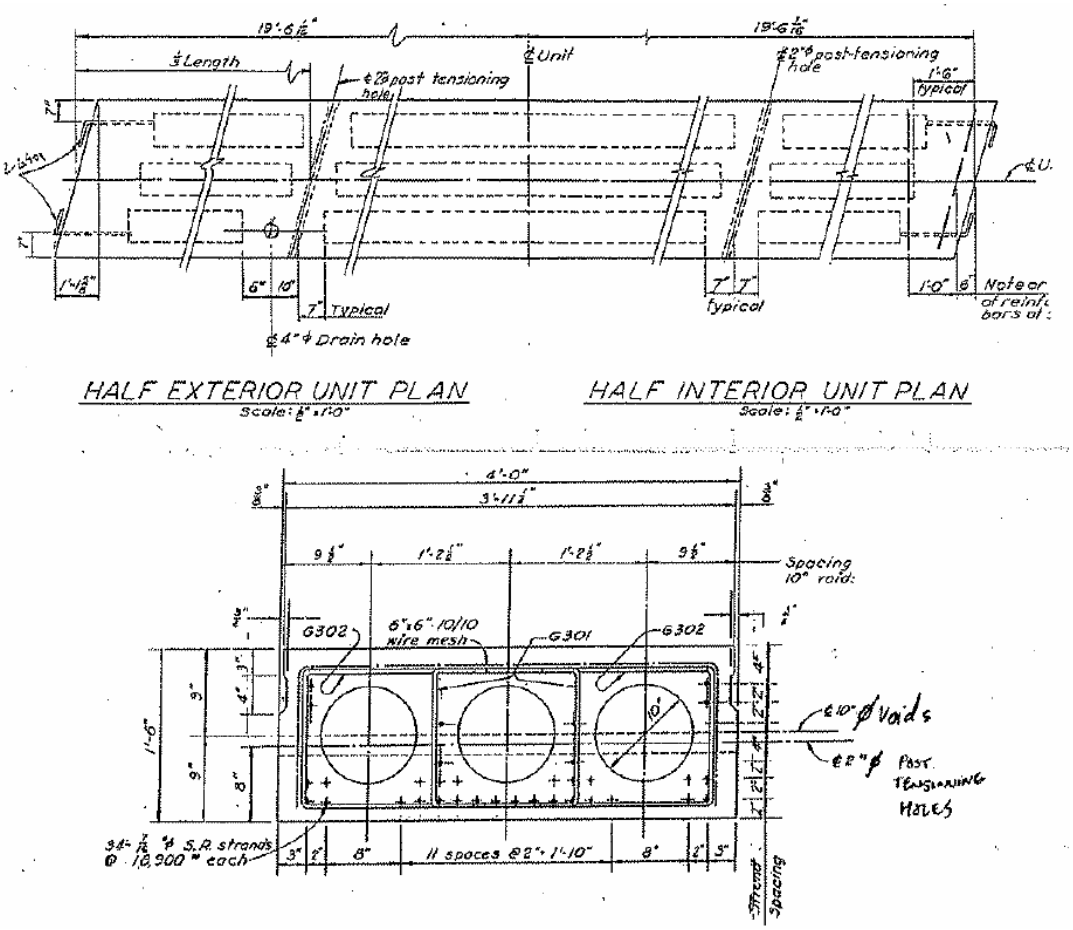

Figure 3: Miami-Dade Sonovoid Bridge Details (Courtesy Bolton Perez & Associates)

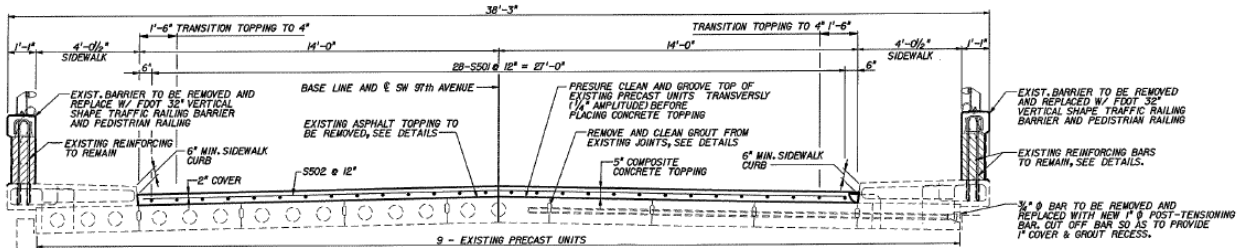

Figure 4: Sonovoid Bridge rehabilitation (Courtesy Bolton Perez & Associates)

12.4. Indiana Bridges

Indiana has a total of 374 non-composite adjacent box beam bridges in their state system and 6905 in their local system. INDOT has recorded many failures occurring during the late 1970's and early 1980's. During the latter part of the 1970's, INDOT was having many problems with their box beam bridges that had asphalt overlay. The concrete on the top of the beams deteriorated so badly that the compressive strength was significantly reduced. As a result, the top flanges buckled resulting in significant flexural deformation.

In 1979 and 1980, INDOT removed all the asphalt on their non-composite box beam bridges. While doing this, they replaced any damaged box beams, and installed a reinforced concrete deck on top of the boxes. Dowels were installed in the box beam flange to ensure integrity and composite action with the newly placed slab. The new concrete slab eliminated seepage of road salts and water from the asphalt surface to the box beams thus eliminating further chloride attack.

The other problem identified with their box beam bridges was that water was trapped in the box voids. The water would freeze, which would cause it to expand, and "blow out" the bottom of the beams. This problem was rectified by drilling drain holes in the bottoms of the beams. INDOT has not reported having any additional problems since 1980 when a large number of box beam bridges were renovated.

12.5. Illinois Bridges

Illinois has a total of 8148 adjacent box beam bridges, 621 of them in the state system with the remaining 7527 in the local system. IDOT has had many problems with single beam failures due to stand corrosion. In 1998, after IDOT suffered a collapse of the fascia beam in this type of bridge, they began surveying similar bridges statewide (Figure 5). The survey identified sixty structures that were in need of rehabilitation. All of these bridges had beams that had spalling, longitudinal cracks, and strand corrosion. After these bridges were examined, IDOT removed three beams from a bridge that had been in service for 30 years. The beams were then evaluated through numerous nondestructive and destructive tests. The test results showed that the transverse tie condition was critical. If the tie remains snug, then cracking in the longitudinal joint will have little effect on the stiffness of the beam. IDOT attempted to identify the condition due to corrosion of the prestressing stands in the three beams, unfortunately the testing was inconclusive.

Figure 5: IDOT Structure 046-0055 Beam Failure [046-0055.ppt]

IDOT has a published element level assessment guideline for superstructure elements. The section on PS Concrete Elements is reproduced below. The guideline is divided into four condition states with 1 being good condition and 4 being poor condition.

Condition State 1: The element shows no deterioration. There may be discoloration, efflorescence, and/or superficial cracking but without affect on strength and/or serviceability. No rust stains visible. Feasible actions: 1) DN

Condition State 2: Minor cracks and spalls may be present and there may be exposed reinforcing with no evidence of corrosion. There is no exposure of the prestress system. Minor rust stains visible. Feasible actions: 1) DN, 2) Seal cracks and minor patch.

Condition State 3: Delaminations and/or spalls may be present. There may be minor exposure but no deterioration of the prestress system. Corrosion of non-prestressed reinforcement may be present but loss of section is incidental and does not significantly affect the strength and/or serviceability of either the element or the bridge. Minor impact damage may have occurred. Working flexural cracks and other miscellaneous cracks with medium rust staining. Structural analysis of more serious problems has found that deficiencies may remain in place until repaired. Feasible actions: 1) DN, 2) Clean steel and patch (and/or seal cracks), 3) Rehabilitate unit

Condition State 4: Delaminations, spalls and corrosion of non-prestressed reinforcement are prevalent. There may also be exposure and deterioration of the prestress system (manifested by loss of bond, broken strands or wire, failed anchorages, etc). There is sufficient concern to warrant an analysis to ascertain the impact on the strength and/or serviceability of either the element or the bridge. Damage due to vehicular collision that may have caused wires to be severed and/or large concrete section loss. Longitudinal joints may have failed. Visible rocking of members may be visible with the passage of live load. Temporary supports may have been installed following structural analysis to allow continual utilization of the structure. Feasible actions: 1) DN, 2) Rehabilitate unit, 3) Replace unit, *Note: For condition state 4, the quantity reported is to equal the entire beam length.*

12.6. Colorado Bridges

Colorado reports that it has zero adjacent prestressed concrete box girder bridges in its state inventory and less than 10 bridges in its local inventory. Colorado Department of Transportation (CDOT) reported only one bridge closure which was the result of a vehicular impact.

The CDOT however has a published guideline which defines inspection conditions for Prestressed Concrete Box Beams. The report is titled:

> Colorado Department of Transportation, "Pontis Bridge Inspection Coding Guide," Denver, CO, October, 1998.

The coding guide divides the condition assessment into four levels CS1 to CS4. With CS1 being good condition and CS4 being poor condition. An excerpt from the manual is provided in Figure 6.

CDOT SUGGESTED CONDITION STATES FOR CRACKS IN PRESTRESSED CONCRETE GIRDERS			
CS1	CS2	CS3	CS4
≤ 0.10 mm (≤ 0.004 in)	0.10 < W ≤ 0.25 (0.004 in) (0.009 in)	0.25 < W ≤ 0.76 (0.009 in) (0.030 in)	W > 0.76 mm (> 0.030 in)

CDOT SUGGESTED CONDITION STATES FOR PERCENT LOSS OF BEARING AREA			
LOSS OF BEARING AREA(%)			
PERCENT LOSS	≤ 10%	10 < % ≤ 20	> 20%
CONDITION STATES	2	3	4

CDOT Note: The total quantity for this element is the product of the length times the number of cells.

Condition State 1 The element shows no deterioration. There may be discoloration, efflorescence, and/or superficial cracking but without effect on strength and/or serviceability.
Feasible actions: 1) DN

Condition State 2 Minor cracks and spalls may be present and there may be exposed reinforcing with no evidence of corrosion. There is no exposure of the prestress system.
Feasible actions: 1) DN
2) Seal cracks minor patch

Condition State 3 Some delaminations and/or spalls may be present. There may be minor exposure but no deterioration of the prestress system. Corrosion of non-prestressed reinforcement may be present but loss of section is incidental and does not significantly affect the strength and/or serviceability of either the element or the bridge.
Feasible actions: 1) DN
2) Clean steel & patch, (&/or seal)

Condition State 4 Delaminations, spalls and corrosion on non-prestressed reinforcement are prevalent. There may also be exposure and deterioration of the prestress system (manifested by loss of bond, broken strands or wire, failed anchorages, etc). There is sufficient concern to warrant an analysis to ascertain the impact on the strength and/or serviceability of either the element or the bridge.
Feasible actions: 1) DN
2) Rehab unit
3) Replace unit

Figure 6: Excerpt from Pontis Coding Guide for PS Concrete Closed Box Girder

12.7. Pennsylvania Bridges

According to the published sufficiency and condition rating database for state and locally owned bridges in Pennsylvania[1] as of December of 2007 there were 25,400 bridges in the state, 3239 of the bridges are classified as prestressed adjacent box girder bridges. One failure occurred at the

[1] http://www.dot.state.pa.us/Internet/web.nsf/Secondary?OpenFrameset&Frame=main&src=InfoBridge?openform

Lake View Drive Bridge over Interstate 70 in 2005. Photos of the failure are included in Figure 7.

Figure 7: Span 3 failure from Pennsylvania Route 1014 over I-70

Pennsylvania Bridges are inspected in accordance with the requirements of PennDOT Bridge Safety Inspection Manual Publication 238. In this document each superstructure is rated on a scale of zero to nine. The general rating system for superstructures is based on the FHWA's Recording and Coding Guide for the Structural Inventory and Appraisal of the Nation's Bridges (FHWA Green Book). The condition levels are as follows

9 = Excellent Condition
8 = Very Good Condition
7 = Good Condition: Some minor problems noted
6 = Satisfactory Condition: Structural elements showing minor deterioration
5 = Fair Condition: Primary structural elements are sound but showing minor cracks and signs of deterioration
4 = Poor Condition: Deterioration of primary structural elements has advanced
3 = Serious Condition: Deterioration has seriously affected the primary structural components
2 = Critical Condition: Deterioration of primary structural components has advanced and bridge will be closely monitored, or closed, until corrective action can be taken.
1 = Imminent Failure Condition: Major deterioration in critical structural components. Bridge is closed but corrective action may put the bridge back into light service.
0 = Failed Condition: Bridge is out of service and beyond corrective action.

To provide clear guidelines for the inspection of Non-Composite Prestressed Concrete Adjacent Box Beams, PennDOT refined their condition rating system. The conditions are summarized in Figure 8. The table is reproduced from PennDOT Bureau of Design Bridge Management System

2 Coding Manual, Publication 100A, July 2007. Under this classification any Bridge with a Condition Rating of 4 or less would deemed Structurally Deficient.

Of the 3239 adjacent box bridges in Pennsylvania two (2) were rated zero, one (1) was rated a one, thirty-one (31) were rated a two, 200 were rated a three, and 358 rated a four. Thus as of December 2007, 592 of the 3239 (or 18% of the) adjacent box beam bridges in Pennsylvania were structurally deficient.

Condition Rating	Percent # Strands Exposed (single beam)	Other Deterioration of P/S Concrete Beams	
9 – Excellent	0%		No cracks, stains or spalls
8 – Very Good	0%		No cracks, stains or spalls
7 – Good	0%		Map cracks and miscellaneous hairline cracks
6 – Satisfactory	0%	Spalls	Minor Spalls/Delaminations, < 5%
		Cracks	Map cracks and misc. hairline cracks
5 – Fair	1-5%	Spalls	Spalls/Delaminations, < 15%
		Transverse Cracks	None
		Longitudinal Cracks	Hairline longitudinal cracks in bottom flange
		Longitudinal Joints	Leakage at joints with light efflorescence
4 - Poor	6-15%	Spalls	Spalls/Delaminations, 15 – 25%
		Transverse Cracks	Hairline flexure cracks across bottom flange
		Longitudinal Cracks	Minor efflorescence and/or minor rust stains
		Longitudinal Joints	Heavy efflorescence and/or minor rust stains
		Transverse Tendons	Loose or heavily rusted
		Web Cracks	Initiation of vertical or diagonal cracks in P/S beam near open joints in barrier (< 3" length)
3 - Serious	15-20%	Spalls	Spalls/Delaminations, > 25%
		Transverse Cracks	Open flexure cracks in bottom flange
		Web Cracks	Vertical or diagonal cracks in P/S beam near open joints in barrier
		Camber	Sagging/Loss of camber
		Transverse Tendons	Broken or missing
2 – Critical	> 20%	All	Any condition worse than detailed above

Figure 8: PennDOT Condition Rating for Non-Composite Adjacent PS Box Beams

To assist in determining load rating values for adjacent box girder bridges PennDOT issued a strike off letter (431-07-08) in September of 2007. The letter provides quantitative recommendations on how to account for strand exposure and corrosion in the load rating calculations. An excerpt from the strike-off letter is included in Figure 9. Note that in accordance with the recommendations provided by the ATLSS research center, strands above and adjacent to a longitudinal crack shall be discounted when estimating the remaining capacity of a deteriorated beam.

6.6.3.3.1I ADJACENT NON-COMPOSITE PRESTRESSED CONCRETE BOX BEAMS Load ratings of beams with deteriorated and/or damaged prestressing strands are to be based on the following procedures: ▪ Visually observed strands + 25% - Deduct 100% of all exposed strands plus an additional 25% (125% of the total area of the exposed strands) from capacity calculations. ▪ Strands adjacent to or intersecting a crack shall be considered ineffective in the region immediately adjacent to the crack. ▪ If significant strand loss is noted (>20%), especially for fascia beams, contact BQAD for further instructions. ▪ For beams with no exposed strands but which appear to have internal damage (as evidenced by bottom flange cracking with rust and/or delamination), contact BQAD for further instructions. ▪ For fascia beams with Capacity/Dead Load < 1.5 or an Operating Rating < 1.5 based on a conventional analysis, an analysis that considers biaxial stresses will be performed by BQAD. ▪ These analysis methods may also be applicable to other pre-stressed box beam bridges	IC 6.6.3.3.1I Based on limited research of beams with longitudinal cracks in the bottom flange, the strand above the crack as well as the two adjacent lower layer stands may be deteriorating. For this condition, a parametric study of strand loss should be performed to determine the sensitivity of beam capacity to strand loss. Because the live load portion of the total load carried by fascia beams is small, the load rating may be > 1.0 and not reflect the marginal capacity above dead load. Thus when Capacity/Dead Load is < 1.5, a more detailed analysis is required.

Figure 9: Excerpt from PennDOT Strike-off letter 431-07-08

12.8. Adjacent PS Concrete Box Beams

Of the 51 departments surveyed by PennDOT 22 responded. The results are summarized in Table 1. According to the responses, Prestressed Concrete Adjacent Box Beam Bridges are used throughout the country. However a greater concentration appears to exist in the Ohio, Indiana, Illinois, and Pennsylvania region. This may be due to the location of large bridge beam producers. For example both Spancrete and New Enterprise Stone and Lime were located in Western Pennsylvania during the construction boom of the 1950s and 1960s. Their geographic location would give them an ideal position for distribution in PA, OH, IN, and IL. Another possible reason for the high concentration may be attributed to regional construction practices. The adjacent beam construction method allows for almost a total precast solution. The construction method eliminates the need to place reinforcing steel and does not require a field placed concrete deck. This would greatly decrease construction schedules which may have been ideal during the construction boom.

It is apparent that where non-composite adjacent box beams are used deterioration is likely to occur. This is attributed to a series of conditions. First an asphalt wearing surface is commonly used without a waterproofing barrier. Thus road salts are able to seep onto the box beams. When the shear key is not completely consolidated the salts also seep onto the web and soffit of the box beams. Over time the chlorides from the road salts penetrate the beams and inevitably lead to corrosion of the strands. To prevent this behavior some transportation groups have removed the asphalt and cast a continuous concrete deck. While this adds a significant dead load the addition of a deck puts a halt to chloride transfer to the strands and greatly increases the service life of the bridge. This method has been successfully used by INDOT and PennDOT District 9.

Table 1: PennDOT Survey Response of States with PS Concrete Adjacent Box Beam Bridges		
State	**State System**	**Local System**
Arizona	100	200
California	99	99
Colorado	0	10
Delaware	43	0
Florida	0	0
Illinois	621	7527
Indiana	10	2739
Maryland	1	101
Minnesota	1	12
Missouri	4	156
New York	4	465
North Dakota	7	212
Ohio	801	2493
Oklahoma	0	0
Oregon	34	94
Pennsylvania	1887	1352
Tennessee	97	295
Utah	6	12
Virginia	199	43
Washington	0	18
Wyoming	0	2
Ontario Canada	3	100
Total	**3917**	**15930**

12.9. Coding and Inspection Methods

As previously discussed there are two primary methods used for condition assessment of PS box beams. The first is based on FHWA recommendations and uses a rating system from 0 to 9 where 9 is excellent condition. Both PennDOT and ODOT have refined this approach and provide additional levels of classification to their inspectors. The classifications are summarized in section 12.2. and 12.7. The second method is based on the Pontis Guideline developed by Colorado DOT and adopted by Illinois DOT. This method is based on a 4 point system with Condition State 1 being good and Condition State 4 being poor. The actions recommended under the Pontis guideline are much more direct than that of the FHWA based inspection guidelines.