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Implementation of Radio Frequency Identification (RFID) Sensors for Monitoring of Bridge Deck Corrosion in Missouri

by

Dr. John J. Myers
Eli Hernandez (PhD Candidate)

**NUTC
R351**

**A National University Transportation Center
at Missouri University of Science and Technology**

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Technical Report Documentation Page

1. Report No. NUTC R351	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Implementation of Radio Frequency Identification (RFID) Sensors for Monitoring of Bridge Deck Corrosion in Missouri		5. Report Date March 2014	
		6. Performing Organization Code	
7. Author/s John J. Myers Eli Hernandez		8. Performing Organization Report No. Project #00042702	
9. Performing Organization Name and Address Center for Transportation Infrastructure and Safety/NUTC program Missouri University of Science and Technology 220 Engineering Research Lab Rolla, MO 65409		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. DTRT06-G-0014	
12. Sponsoring Organization Name and Address U.S. Department of Transportation Research and Innovative Technology Administration 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered Final	
		14. Sponsoring Agency Code	
15. Supplementary Notes			
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17. Key Words Non Destructive Evaluation, RFID Sensors, Corrosion Detection, Bridge Implementation		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
19. Security Classification (of this report) unclassified	20. Security Classification (of this page) unclassified	21. No. Of Pages 31	22. Price

Final Report for
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Prepared by:

Dr. John J. Myers

Eli Hernandez (PhD Candidate)

Missouri University of Science & Technology
Department of Civil, Architectural & Environmental Engineering

March 2014

ABSTRACT

Chloride ion ingress is an important parameter that helps estimate the durability and service life of reinforced concrete (RC) and prestress concrete (PC) structures, especially in those structures exposed to marine environments and salts applied during the winter season for traffic safety. Current techniques used to detect chloride content and monitor the level of corrosion in RC and PC structures, such as acoustic emission (AE), fiber optics, and electrochemical measurements, are time consuming, and invasive. In addition, they require external power sources, complex test setups, are expensive to implement, and often, it is difficult to interpret the data recorded in the field. In an effort to overcome these restrictions, an inexpensive, wireless corrosion detector sensor based on commercial radio frequency identification (RFID) technology that does not need to be powered by a local source of energy, has been developed by an Oklahoma State University's research team. The purpose of the first phase of this project was to implement this innovative RFID corrosion sensor into a new bridge construction to collect data during monitoring to study both the reliability and field performance of the sensor in-situ and under laboratory conditions. The laboratory work attempted to correlate the sensor's sensitivity to the level of corrosion in the structure. Phase II of this work will be focused on the long-term monitoring of the sensors installed in the field for a period of approximately 10 years.

ACKNOWLEDGEMENT

This project was made possible with the financial support received from the National University Transportation Center at Missouri University of Science and Technology in Rolla, Missouri. Grateful acknowledge is made to Dr. Tyler Ley, from Oklahoma State University, for his generous contribution by providing the RFID corrosion sensors used in this project. The authors would like to thank the Missouri Department of Transportation for their support during the implementation of this radio frequency identification (RFID) based corrosion sensors, object of this study, in the field. The authors also thank to the Missouri S&T Department of Civil, Architecture and Environmental (CArE) Engineering's efforts through Brian Swift who developed the RFID sensor's data acquisition system. Special thanks are given to the Missouri S&T CArE Engineering Department's staff members Gary Abbott, and Delbert Hampton, as well as the graduate students Alex Griffith, Hayder Alghazali, Wei Wang, Benjamin Gliha, and Amanda Steele for their assistance during the different stages of the project.

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1 INTRODUCTION

1.1 BACKGROUND

Corrosion is a mechanism that gradually destroys a material as a result of the chemical reactions produced within its surrounding environment that can cause severe damages and expenses to every industry sector in the nation. A study, entitled "Corrosion Costs and Preventive Strategies in the United States", was assigned to CC Technologies Laboratories, Inc. in 1999. The initiative was a cooperative agreement between the Federal Highway Administration (FHWA) and NACE International entrusted by the U.S. Congress. In 2002, the results of this break-through 2-year research were unveiled revealing that the direct costs associated with metallic corrosion nearly every U.S. industry sector were about \$ 276 billion representing 3.1% of the nation's Gross Domestic Product (GDP) [1]. Furthermore, the same study estimated the annual direct cost of corrosion related to highway bridges to be \$8.3 billion, and reported that indirect costs to the user due to traffic delays and loss of productivity were nearly 10 times the direct costs. Within the preventive strategies summarized by this report, an important effort to develop and implement optimized corrosion control practices was remarked to help decrease corrosion direct and indirect costs that impact daily life and the economic health and security of the nation.

Chloride ion ingress is an important aspect of the durability design and maintenance of reinforced concrete (RC) and prestress concrete (PC) structures, especially in regions of marine environments and where salts are employed during the winter season to assure traffic. Current techniques to detect chloride content are time consuming and invasive. Core samples need to be collected, and lane closures are necessary causing traffic delays. A potential non-destructive detection method will be a break-through to the advancement of structural health monitoring and durability of infrastructure facilities [2]. Important efforts have been conducted applying acoustic emission (AE), fiber optics, electrochemical measurements among others technique used to detect the corrosion onset and to monitor its spread within RC and PC members. However, some of these methods are expensive; require complex test setups, external power sources, and often it is difficult to interpret the data they collect. These restrictions

have prevented their widespread utilization to assure a better corrosion management control. In an effort to overcome these limitations, a research team from Oklahoma State University has developed a passive, inexpensive, wireless corrosion detector sensor based on commercial radio frequency identification (RFID) technology that does not need a local source of energy.

The following sections describe the technology used on the first phase of the implementation of this innovative RFID corrosion sensor into a new bridge construction. The purpose of this stage was to study both the reliability and field performance of the sensor in-situ and under laboratory conditions. The laboratory work intended to correlate the sensor's sensitivity to the level of corrosion in the structure. The second phase of this work will involve the long-term monitoring of the sensors installed in the field for a period of a decade.

1.2 LITERATURE REVIEW

1.2.1 RFID Tag Technology

Radio frequency identification (RFID) tags are wireless, non-contact electronic devices that are employed to identify and track goods in many different industries. During the last decades, RFID tags have become very popular thanks to the great diversity of ranges offered to collect information electronically stored in their on-board electronic processors or chips, and the affordable cost of this technology. According to the way RFID tags are powered, they can be categorized as active or passive tags. An active RFID tag is powered by a local source of energy, such as a battery, and can be read at a hundreds of yards away from the tag's interrogator. Passive RFID tags do not use batteries; instead, they are powered by radio frequency radiation to read their data at very short ranges (usually a few inches or feet from the tag's reader). An RFID tag's reader is necessary to collect the data stored in the tag's processor by a process called load modulation. This process involves sending out an interrogator signal from the reader's antenna to the tag's transponder and receiving a response back from the transponder to the receiving antenna of the reader. The RFID reader decodes the current modulation received from the tag and obtains a tag's identity that contains information that can be easily interpreted and written into a text file by a data acquisition system (DAS).

1.2.2 RFID Technology Based Corrosion Sensors

For this implementation project, a passive RFID based corrosion sensor was employed to detect the chloride salt concentration that initiates the onset of corrosion in the reinforcing steel of concrete members. Figure 1.1 shows the body of a second generation prototype of the RFID corrosion sensor developed by the Oklahoma State University's research team led by Dr. Tyler Ley [2, 3]. The body of the sensor is about the size of a quarter.

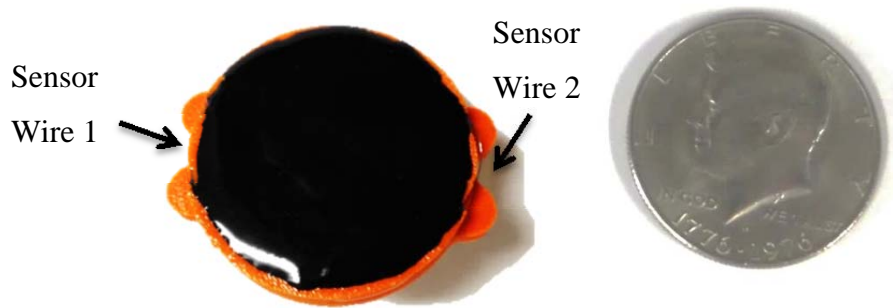


Figure 1.1. RFID Based Corrosion Sensors (Body)

The sensor's impermeable external body holds two external 99.99% pure iron wires of different diameter that corrode as conventional reinforcing steel [2]. In addition, the external body houses an internal circuit board that registers the voltage variations of the wire links of the sensor when an RFID reader is used to manually scan the chip's data. The RFID corrosion sensor does not rate the mass loss or corrosion rate of reinforcing steel [2]. Instead, each external iron wire acts as a trigger mechanism that fails when the content of chloride ingress reaches a critical value in the sensor's surrounding concrete.

This function provides information and alerts that can be interpreted or justify as a possible maintenance or repair action that should be undertaken to restore an RC or PC structure's integrity. The operation of the RFID Sensor, developed by Ley et al. [3], consists of transmitting a interrogator signal from a commercial RFID reader to the RFID tag via a magnetic induction process (also called radio frequency radiation).

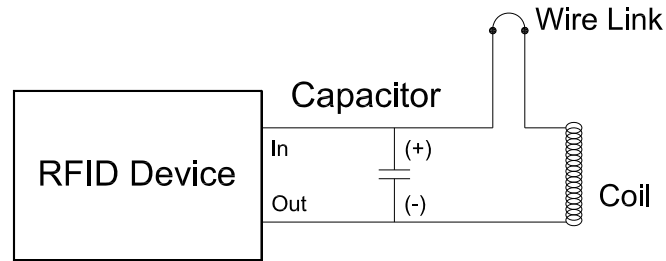


Figure 1.2. RFID-Based Corrosion Sensor Block Diagram (Ley et al. [2])

By sending this magnetic signal, the alternating current in the tag reader's coil induces a current in the tank circuit of the tag. The voltage across the resonance circuit is rectified and filtered by the capacitor (Figure 1.2). The chip's microcontrollers are powered and the circuit processor reads the voltage at the terminal denoted as "In" (see Figure 1.2). Then, the signals collected by the RFID reader are converted into binary readings that contain information after evaluating if the link is still conductive or not. The RFID reader decodes and translates the modulation received from the tag into an RFID tag ID reading. If the wire link is intact, i.e. the measured voltage is the initial predicted value, the sensor responds with an RFID value. Otherwise, if a voltage change is detected, a different RFID value is sent back to the reader.

Unlike the first generation of the RFID corrosion sensor, developed by Ley et al. [2], which only had an iron wire link, its second version was provided with two wire links. Each wire allows detecting a different chloride concentration. This improved feature has a significant implication; for instance, the thinner wire detects the chloride content that initiates the corrosion, and the second wire could be employed to report a critical chloride concentration that produces an important loss of the reinforcing or prestressing steel area of a concrete member.

Prior to the installation of any corrosion sensor in the field or laboratory, the diameter of each of the wire links was verified. Figure 1.3a shows the Stereo Microscope brand "Hirox" used to obtain the wire's dimensions of each corrosion sensor. Several measurements were taken, and the average diameter of the thinner and thicker wire was obtained as 0.065 mm (65 μ m) and 0.100 mm (100 μ m), respectively. Figure 1.3 b shows some of the readings obtained for the thinner RFID tag's wire link.



a) Hiox Stereo Microscope

b) Iron Wires Dimension

Figure 1.3. Verification of RFID Corrosion Sensor's Iron Wire Diameter

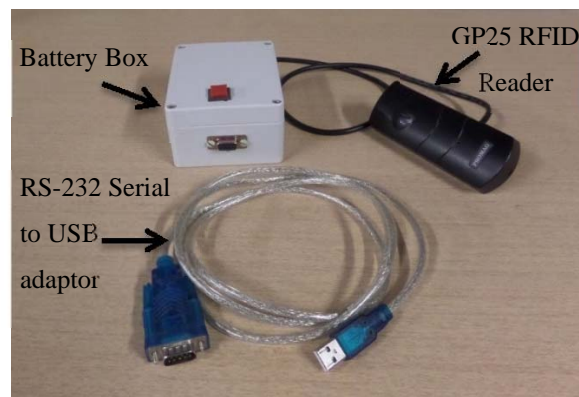
1.3 RFID CORROSION SENSOR'S DATA ACQUISITION

1.3.1 Data Acquisition Hardware

The data acquisition hardware consists of a Dell Latitude E6520 Laptop, with an Intel® Core™ i7-2620M CPU, 2.7 GHz Processor, and a 15-in HD Monitor (Figure 1.4a), and an RFID scanning system (Figure 1.4b). The RFID scanning system has three main components: an RS-232 Serial to USB adaptor cable, a GP25 proximity RFID reader (model EM4200/4102), and a battery box.



a) Dell Laptop



b) RFID Scanning System

Figure 1.4. RFID Data Acquisition Hardware

The GP25 RFID reader is a low frequency component, high-performance, proximity reader featuring a long range data acquisition that can be used within a distance of 4 in (100 mm) from the corrosion sensor. In addition, this unit was configured to the interface format Clock/Data and RS-232 serial ASCII output. The battery box houses eight 1.5-volt AA batteries installed to supply power to the RFID reader. The GP 25 RFID reader passes the 9-pin RS-232 wiring through the battery box, so the data is carried from the RFID reader to the laptop's data acquisition software to be manipulated. The battery momentarily energizes the RFID reader when the activation switch is pressed down (red button of power box in Figure 1.4). The functioning of the data acquisition hardware was described in section 1.2.2.

1.3.2 Data Acquisition Software (Programming and Data Collection)

The data acquisition software (DAS) is the user's interface that orders the RFID reader what information to collect and how it should be collected from the RFID sensor tag. LabVIEW™ (2013) was the graphical programming language used to write and compile the software "Serial Reader.vi" that controls the DAS equipment. Figure 1.5 shows the user's interface of "Serial Reader.vi" that is utilized to control the RFID reader and to receive the output data from the sensor tag in the form of RFID code IDs.

The process to manually collect data from the corrosion sensors is as follows:

- a) Connect the RS-232 serial to USB adaptor to the RFID power box serial port and to the laptop's USB port
- b) In the "baud rate (9600)" data box, enter "9600" as the speed rate to collect the information (see Figure 1.5)
- c) From the drop down menu "VISA resource name", select the communication port where the RS-232 adaptor was connected (e.g. select "COM1" or "COM2")
- d) In the "Data File with Path" data box, type the name of the file and folder which the output data will be saved on
- e) Click on the "Running" icon (black arrow icon) of the toolbar menu to synchronize the data acquisition software and hardware to begin collecting data
- f) Leave the rest of the default options as shown in Figure 1.5
- g) Click on the "Run Continuously" icon of the toolbar, to start collecting readings,

- h) To begin collecting data, press down the activation switch (red button of the DAS power box, see Figure 1.4b) and pass the RFID reader over the concrete area where the RFID corrosion sensor is embedded. Remember that the RFID reader's range works within a range of 4 in. (100 mm) as mentioned in section 1.3.1

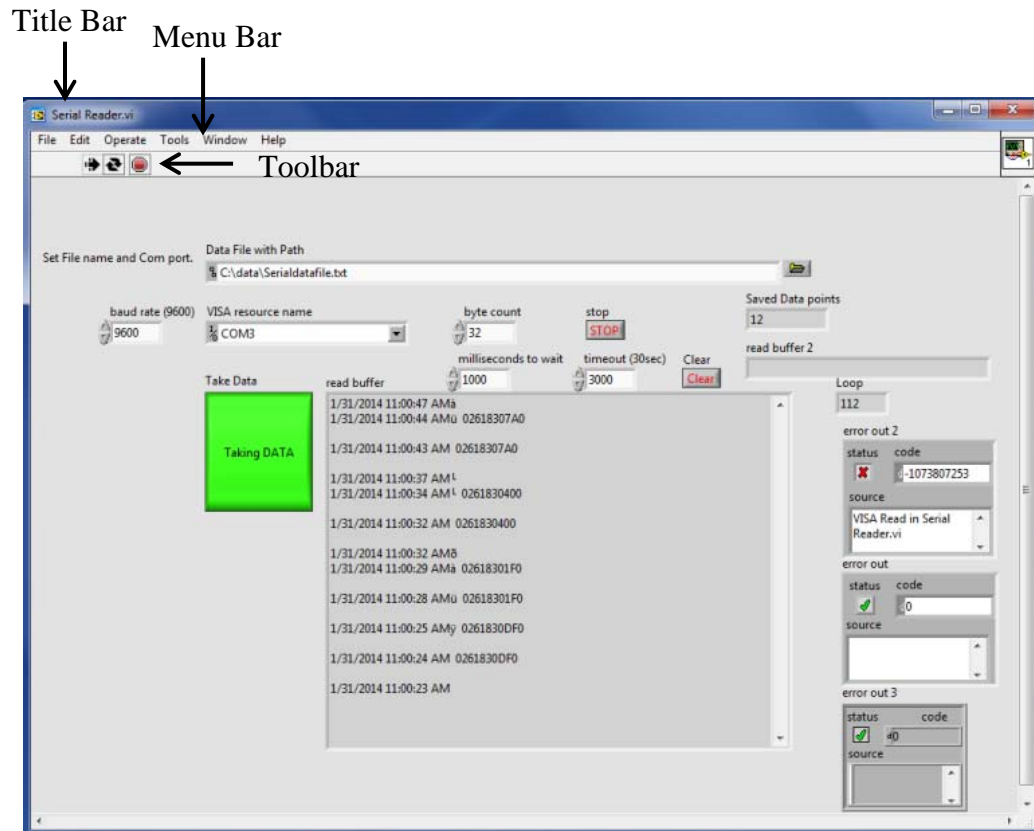


Figure 1.5. RFID DAS Software (User's Interface)

- i) To stop collecting data, click on the "Abort Execution" icon (red circle icon) of the toolbar menu

Figure 1.6 shows an output file written by the data acquisition software "Serial Reader.vi". The RFID reader collects an RFID ID code each time the sensor is scanned and sends that reading to "Serial Reader.vi". Then, the RFID ID code is written into the output file (.txt format). The file can be edited by any word processor such as "Notepad[®]" or "Word[®]".



Figure 1.6. RFID Sensor's Output File

The first, second and third columns of the data file represent the date, time, and RFID ID codes obtained by the data acquisition system. Figure 1.7 shows a typical RFID ID code.

Digit Value	→	<u>0</u>	<u>2</u>	<u>6</u>	<u>1</u>	<u>8</u>	<u>3</u>	<u>0</u>	<u>D</u>	<u>F</u>	<u>0</u>
Digit Position	→	1	2	3	4	5	6	7	8	9	10

Figure 1.7. Typical RFID ID Code

From the RFID ID code of Figure 1.7, the following information is extracted:

- Digits 1 and 2 represent the revision number of the RFID tag. For this case, the "02" indicates the RFID sensor belongs to the second prototype generation
- Digits 3 through 9 contain a fixed tag's ID, in other words, this is the sensor's serial or identification. For this reading, the tag's ID is: **61830DF**
- Digit 10 is the decoded response that the RFID tag sends through the reader to the data acquisition software. It indicates the status of the sensors' wire links. This digit can take four different values. A value equal to zero (0) means that both iron wires are intact; therefore, no critical chloride content is surrounding the sensor. A value of one (1) or two (2) means that the thinner or thicker iron wire has failed, respectively (i.e. the resistance measured by the sensor is greater or equal than about 500 ohm). Finally, a value of 4 means that both sensors' link wires have failed.

2 FIELD AND LAB RESPONSE OF RFID CORROSION SENSORS

The work conducted on this project involved the application of six RFID corrosion sensors of the second generation to study their reliability and field performance in-situ and under laboratory conditions. Two RFID sensors were installed during Bridge A7957's RC deck construction and four others were embedded in specimens to be monitored in the lab. The first two lab specimens were fabricated using the same concrete mix placed on Bridge A7957's RC deck and the last two by using a modified version of this concrete mix. The long-term monitoring of the six RFID corrosion sensors began with installation of the sensors within the RC bridge deck and each set of two specimens were cast, and last until both RFID wire links of each sensor fail. The main objective is to confirm that the wire links can detect the ingress of corrosive agents and trigger at repeatable chloride concentration values.

2.1 FIELD IMPLEMENTATION

As part of a two lane expansion project of highway 50, overtaken by the Missouri Department of Transportation (MoDOT), Bridge A7957 was built between the summer and fall of 2013. This new bridge overpasses Maries River, West Linn, in Osage County, Missouri. In the following sections, information related to Bridge A7957, and its sensors' installation details are presented.

2.1.1 DESCRIPTION OF BRIDGE A7957

Bridge A7957 is a three-span (100ft., 120ft., and 100 ft.), continuous, slab-on-precast PC girders bridge (see Figure 2.1 and Figure 2.2). Each span, composed of four PC NU 53 girders (see Figure 2.3), was made of different type of concrete grades. The girders on the first span were fabricated using conventional concrete (CC) of a design compressive strength equal to 8,000 psi (55.2 MPa). The second span uses high-strength, self-consolidated-concrete (HS-SCC) of a nominal compressive strength equal to 10,000 psi (68.9 MPa). The girders of the last span were constructed with self-consolidated-concrete (SCC) of a design compressive strength equal to 8,000 psi (55.2 MPa).

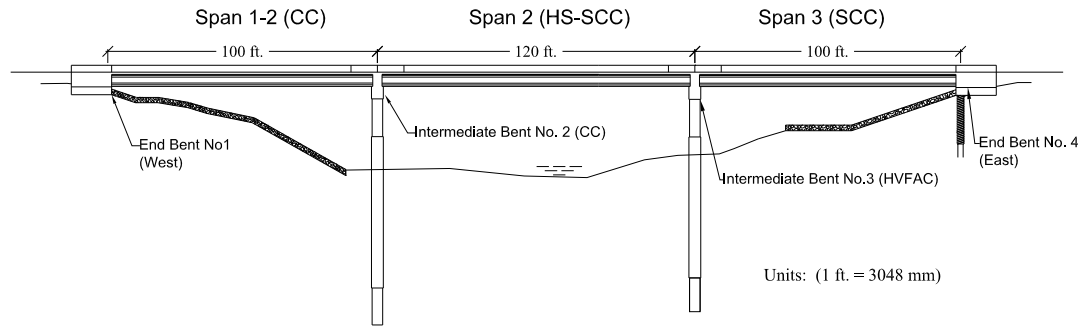


Figure 2.1. Bridge A7957 Elevation

Precast PC panels extend between the top flanges of the PC girders in the transverse direction underneath a cast-in-place (CIP) RC deck (see Figure 2.3). The concrete mix used to cast the deck is of a nominal compressive strength equal to 4,000 psi.

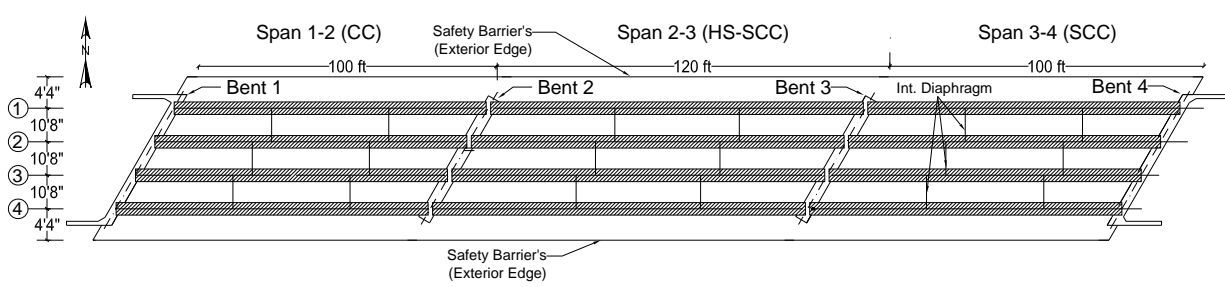


Figure 2.2. Bridge A7957 Plan View

Two intermediate bents and two end abutments support the superstructure (see Figure 2.1). Intermediate bent 2 was cast with conventional concrete of 3,000 psi (20.7 MPa) nominal compressive strength, and intermediate bent 3 was cast with high-volume-fly-ash concrete (HVFAC) with a nominal compressive strength of 4,000 psi (27.6 MPa) (see Figure 2.1).

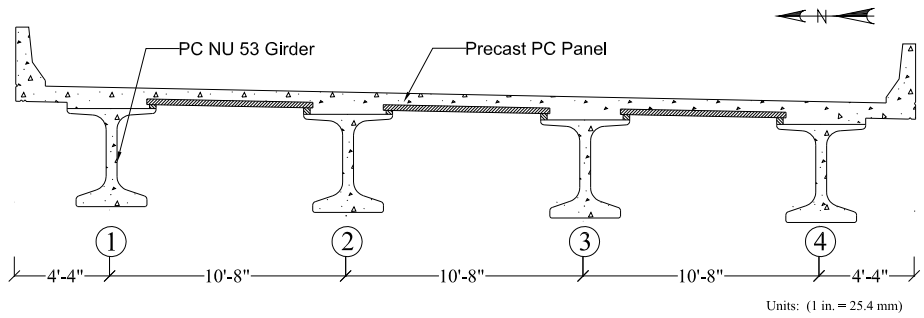


Figure 2.3. Bridge A7957 Cross Section

2.1.2 BRIDGE A7957 INSTRUMENTATION SETUP

As part of this implementation project in the field, two RFID corrosion sensors, identified in Figure 2.4 as RFID corrosion sensor 1 and 2, were embedded at two different locations within the south side of Bridge A7957's deck to detect different chloride concentration levels (see Figure 2.5 and Figure 2.6a).

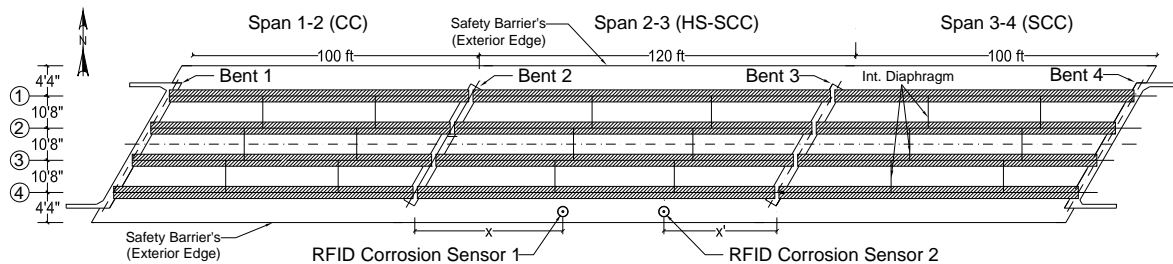


Figure 2.4. Bridge A7957 RFID Corrosion Sensors Installation (Plan View)

Table 2-1 presents the location's coordinates within the RC deck where these sensors were installed. Sensor 1 (tag ID 61830B5) was placed 44 ft. 9in (13.7 m) from the center line of bent 2 (see Figure 2.4), along the same direction of the safety barriers' principal axis. This sensor was installed a 0.25 in. (6 mm) from the top surface of the deck, at a distance of 22.00 in (559 mm) from the exterior edge of the safety barrier (see Figure 2.5).

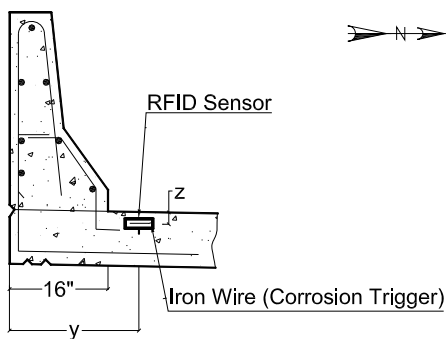


Figure 2.5. Bridge A7957 RFID Corrosion Sensors Installation (Elevation)

Sensor 2 (tag ID 6183035) was placed 45ft 3in from the center line of bent 3, along the same direction of the safety barriers principal axis. This sensor was installed a 0.50 in. (13 mm) from the top surface of the deck, and at distance of 18.25 in (464 mm)

from the exterior edge of the safety barrier (as reported in Table 2-1). Figure 2.6b shows the finished appearance of Bridge A7957's RC deck after the concrete placement.

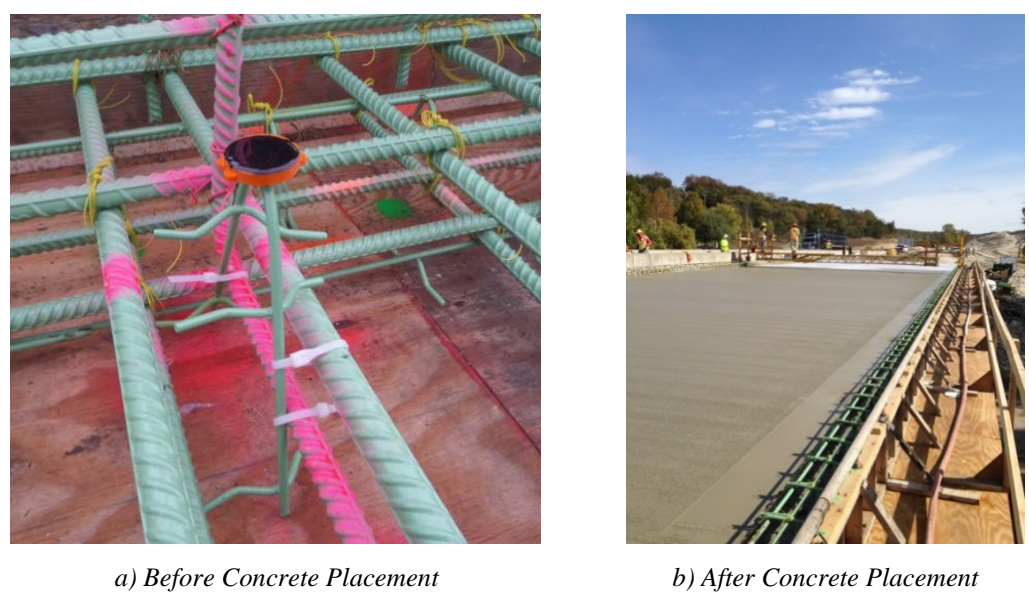


Figure 2.6. RFID Tag's Installation on CIP-RC Deck of Bridge A7957

Table 2-1. RFID Sensors' ID and Location's Coordinates Bridge A7957's Deck

Sensor ID	RFID ID	X / X'	Y	Z
1	61830B5	44'9" / 75'3"	22"	1/4"
2	6183035	74'9" / 45'3"	18 1/4"	1/2"

X, X', Y, Z= RFID sensors' coordinates within the reinforced concrete deck
Conversion: 1 in. = 25.4 mm, 1 ft. = 0.3048 m

2.2 PONDING CHLORIDE SPECIMENS

Four chloride ponding test specimens were fabricated to investigate the reliability and response of the RFID corrosion sensors under lab conditions. Two specimens were fabricated for two different concrete mixes. This was attempted to obtain more information to correlate the chloride concentration content that produces the failure of the RFID wires links and the time these failures occurred. The following sections described the properties of the concrete mixes used to cast these ponding chloride specimens, details about the specimens preparation and fabrication, corrosion sensors' installation, as well as the tests performed in the lab is provided.

2.2.1 Concrete Mix Properties (Test Specimen 1 and 2)

The concrete mix used for Bridge A7957 deck's concrete placement was used to cast the ponding chloride specimens 1 and 2. MoDOT designates it as Mod B-2 (Modified B-2). The material proportions of this concrete mix are specified in Table 2-2. The amount of sand, rock and water were adjusted to account for the aggregates' moist content during concrete's placement. The first row indicates the design proportions while the second row indicates the batch proportions used to prepare the mix in the ready mix plant.

Table 2-2. Concrete Mix Proportions (Field Ponding Specimens 1&2)

Concrete Mix ID	w/cm	Air (%)	Slump (in)	Unit weight per volume (lbs/yd ³)						
				<i>Cem.</i>	<i>Fly Ash</i>	<i>Sand</i>	<i>Rock</i>	<i>Water</i>	<i>Davavair 1400^P</i>	<i>Adva 140M^{PP}</i>
<i>MOD B-2⁽¹⁾</i>	0.42	6-10	-	450	150	1170	1895	220	4.5	2.0
<i>MOD B-2⁽²⁾</i>	0.42	8.3	5.75	450	150	1214	1932	175	4.5	2.0

¹: Design proportions; ²: Batch proportions.

^P = oz. /yd³; ^{PP} = oz. / 100 lb. of cement.

Conversion: 1 in. = 25.4 mm, 1 lb. /yd. = 0.593 kg/m³

2.2.2 Concrete Mix Properties (Test Specimen 3 and 4)

Concrete mix CSEN2LAB001, used to cast ponding chloride specimens 3 and 4, was a variation of concrete mix Mod B-2 use for Bridge A7957's deck. The material proportions used to produce this concrete mix are reported in Table 2-3 and are identified as batch proportions. The design proportions (before any water content adjustment) are also showed.

Table 2-3. Concrete Mix Proportions (Laboratory Ponding Specimens 3&4)

Concrete Mix ID	w/cm	Air (%)	Slump (in)	Unit weight per volume (lbs/yd ³)						
				<i>Cem.</i>	<i>Fly Ash</i>	<i>Sand</i>	<i>Rock</i>	<i>Water</i>	<i>Davavair 1400^P</i>	<i>Adva 140^{PP}</i>
<i>CSEN2LAB001⁽¹⁾</i>	0.5	9.0	-	450	150	1170	1895	300	6.0	2.0
<i>CSEN2LAB001⁽²⁾</i>	0.5	9.0	8.00	450	150	1160	1860	285.5	6.0	2.0

¹: Design proportions; ²: Batch proportions

^P = oz. /yd³; ^{PP} = oz. / 100 lb. of cement.

Conversion: 1 in. = 25.4 mm, 1 lb/yd³ = 0.593 kg/m³

The compressive strength as a function of time was plotted obtained for both concrete mixes in the chart of Figure 2.7. The decreasing in the compressive strength of concrete mix CSEN2LAB001 was obtained by increasing the w/cm ratio and air content of the concrete mix used in the Bridge's A7957 deck. The original concrete mix was modified to produce a higher permeable and less resistant material to investigate the RFID sensor's sensitivity and performance under these different conditions.

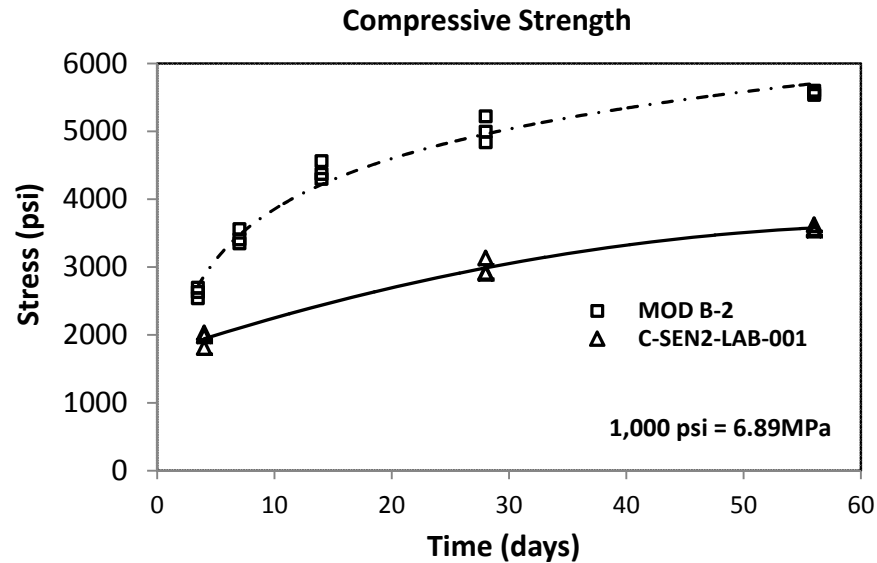


Figure 2.7. Ponding Specimen Concrete's Compressive Strength

2.2.3 Specimens Fabrication

The ponding chloride specimens (see Figure 2.8) were fabricated according to ASTM C 1543-10, "Standard Test Method for Determining the Penetration of Chloride Ion into Concrete Ponding" [4]. The test requires that the specimens have a surface area of at least 45.6 in^2 (0.030 m^2). The specimens should be at least $3.54 \pm 0.6 \text{ in}$ ($90 \pm 15 \text{ mm}$) tall. The specimens created for the ponding tests measured 18 in. (457 mm) wide by 18 in. (457 mm) long by 4 in. (102 mm) tall. The test procedure required a dike along the top edge that should be at least 0.79 in. (20 mm) high. To build the dike with such characteristics, a 0.875 in.-thick (22 mm) foam panel of 16 in. (406 mm) by 16 in. (406 mm) plan dimensions was placed on a sheet of plywood that would serve as the base of the mold. Walls made of 2 in. (51 mm) by 4 in. (102 mm) pieces of wood were connected to a wood panel to obtain the overall dimension of 18 in. (457 mm) by 18 in. (457 mm).

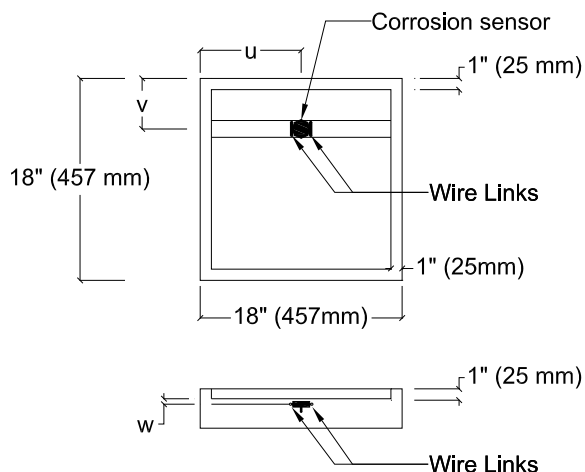


Figure 2.8. Ponding Test Specimen Fabrication and Sensors' Installation Details

The final dimensions of the specimens are shown in Figure 2.8. The foam shaped the reservoir for the chloride solution when the concrete was cast in the molds. Before casting the concrete, an RFID chloride sensor (Figure 1.1) was installed in the mold as shown in Figure 2.9a. The details of the locations the corrosion sensors were installed within the specimens are given in Table 2-4 (see Figure 2.8 for additional reference).

Table 2-4. RFID Sensors' ID Coordinate Locations within Ponding Specimens

Sensor ID	RFID ID	Specimen ID	Concrete Mix ID	u (in.)	v (in.)	w (in.)
3	61830DF	C-SEN2-001-F	MOD B-2	9	4½	¼
4	618301F	C-SEN2-002-F	MOD B-2	9	4½	½
5	6183040	C-SEN2-003-L	C-SEN2-LAB-001	9	4½	½
6	618307A	C-SEN2-004-L	C-SEN2-LAB-001	9	4½	1

u, v, w = coordinates that define the location of the RFID tag sensors within the Ponding Specimens (see Figure 2.8).
Conversion: 1 in. = 25 mm

The concrete was placed and consolidated in the molds according to ASTM C192 “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory” [5]. Figure 2.9b shows two ponding specimens after removing the molds. After 24 hours, the concrete specimens were de-molded and placed in a moist cure room at 100% relative humidity (Figure 2.9c). After 14 days of moist curing, the specimens were transported to a temperature and humidity controlled environment where they would dry cure at 75°F

(23.8°C) and 65% relative humidity for another 14 days. After 28 days of moist curing, the specimens began the chloride ponding test.



a) Molds and RFID Sensors' Installation Detail



b) Ponding Test Specimens after Removing the Molds



c) Moist Curing of Ponding Chloride Test Specimens

Figure 2.9. Ponding Chloride Test Specimens Preparation

2.2.4 Ponding Test Procedure

The test procedure consisted on pouring a 5% by weight sodium chloride solution into the ponding specimen reservoir. The solution's depth should be at least 0.6 ± 0.2 in. (15 ± 5 mm). Figure 2.10 shows a typical ponded specimen. When the necessary amount of solution was poured into the reservoir, the concrete specimens were covered with plastic sheeting, and the sheets were secured with elastic bands to prevent the evaporation of the solution.



Figure 2.10. Ponding Chloride Test Specimen with 5% Sodium Chloride Solution

Every two weeks, the specimens were inspected to ensure that a proper solution level was maintained. If the reservoir depth was low, additional solution was added. After 60 days of ponding, the reservoir was vacuumed dry and fresh solution was added. The plastic sheeting was replaced and the specimens were monitored every two weeks. After another 60 days, the chloride solution was vacuumed off and the specimen allowed to air dry. This procedure was repeated until one of the RFID wire links failed. In that event, a core was taken from the center of the specimen to determine its chloride concentration. When the second sensor's wire link failed, another core was taken to be analyzed as well. The following section presents the procedure followed to analyze the cores extracted from the ponding specimens.

3 RESULTS AND DISCUSSION

3.1 BRIDGE A7957 RESULTS

Table 3-1 presents a set of processed data collected from Bridge A7957's RFID sensors by the RFID data acquisition system on November 8, 2013.

Table 3-1. Bridge A7957 RFID Sensor's Readings

DATE	TIME	RFID ID CODE
11/8/2013	10:30:40	0261830B50
11/8/2013	10:32:25	0261830350

The RFID ID codes, given in Table 3-1, codes correspond to the description given in section 1.3.2 (See Figure 1.7). At this time, none of the RFID sensors installed in Bridge A7957's RC deck has reported a wire link failure. That can be noticed from the readings of Table 3-1. For both of them the last digit of the RFID ID code is equal to zero (0). Continuous monitoring will be continuously overtaken, every three months, during the next decade to detect a loss or failure of the wire links in any of the sensors. In such event, core samples will be collected to determine the chloride concentration that produced this rupture of the link. Field results will be correlated and compared to results obtained from the laboratory specimens. Figure 3.2 shows the collection of data for one of the RFID sensors installed on Bridge A7957 RC deck according to the details of Figure 2.4 and Figure 2.5.



Figure 3.1. Bridge A7957 Data Acquisition

3.2 PONDING SPECIMENS

Table 3-2 reports a set of processed data collected for all the sensors that were installed within the lab specimens. The data corresponds to the inspection conducted on February 20, 2014.

Table 3-2. Ponding Specimen RFID Sensor's Readings

DATE	TIME	RFID ID CODE
2/20/2014	4 1:34:52	0261830DF0
2/20/2014	4 1:36:14	02618301F0
2/20/2014	4 1:36:38	0261830400
2/20/2014	4 1:36:55	02618307A0

At this time, none of the RFID sensors installed within the specimens have experienced a wire link failure. As in the case of the RFID sensors installed within the RC deck of Bridge A7957, the last digit of the readings is equal to zero (0) which indicates that the sensor wires are active. Continuous monitoring is being overtaken every week and will continue during the next months to detect a change of the wire link status of any sensors. This monitoring phase will be executed until both wires of each sensor have failed. Core samples will be collected when each sensor wire link fail. Then, the chloride concentration will be obtained to probe that the wire links trigger at the same chloride concentration.

The APPENDIX presents the complete set of raw data obtained from the regular inspections conducted on the six sensors since their installation.



Figure 3.2. Ponding Chloride Test Specimens' Data Acquisition

4 CONCLUDING REMARKS

During the first phase of the present work, the following preliminary conclusions can be drawn:

- The RFID corrosion sensors' implementation has been efficiently conducted in the field and the laboratory to study both the reliability and field performance of the sensor in-situ and under laboratory conditions.
- An RFID data acquisition system, composed of an RFID scanning device and RFID data acquisition software, have been developed to collect data from the RFID corrosion sensors.
- Chloride ponding specimens were fabricated in the field and laboratory to determine if the sensors' wires trigger at similar chloride concentrations.
- The second phase of this work will be focused on the long-term monitoring of the sensors installed in the RC deck of Bridge A7957 for a period of approximately 10 years or until some change in the sensors circuit is detected.
- The RFID corrosion sensor prototype used on this implementation project does not determine the rate of mass loss or corrosion rate of reinforcing steel. Instead, it is a promising and effective device that can be used to determine the chloride ingress that activates the onset of corrosion in reinforcing and prestressing steel of concrete members.

5 APPENDIX

The following set of raw data was collected by the RFID data acquisition system between November 2013 and February 2014. The readings correspond to the six sensors installed in the field and laboratory specimens.

DATE	TIME	RFID ID CODE
11/6/2013	3:20:11	PM0261830DF0
11/6/2013	3:20:18	PM02618301F0
11/8/2013	10:30:40	AM0261830B50
11/8/2013	10:32:25	AMü0261830350
1/8/2014	3:49:06	AM0261830DF0
1/8/2014	3:50:13	AM02618301F0
1/8/2014	3:51:29	AM0261830400
1/8/2014	3:53:09	AM02618307A0
1/29/2014	10:58:49	AMp02618301F0
1/29/2014	10:58:57	AM0261830400
1/29/2014	10:58:59	AMü02618307A0
1/29/2014	11:00:44	AM0261830DF0
1/31/2014	11:00:24	AM0261830DF0
1/31/2014	11:00:29	AM02618301F0
1/31/2014	11:00:32	AM0261830400
1/31/2014	11:00:43	AM02618307A0
2/6/2014	11:42:31	AM0261830DF0
2/6/2014	11:42:41	AM02618301F0
2/6/2014	11:42:48	AM0261830400
2/6/2014	11:42:56	AM02618307A0
2/13/201	4 9:40:01	AM0261830DF0
2/13/201	4 9:40:11	AM02618301F0
2/13/201	4 9:40:24	AM0261830400
2/13/201	4 9:40:33	AM02618307A0
2/20/201	4 1:34:52	PMđ0261830DF0
2/20/201	4 1:36:14	PM02618301F0
2/20/201	4 1:36:38	PMđ0261830400
2/20/201	4 1:36:55	PM02618307A0

6 REFERENCES

- [1] G. Koch, M. Brongers, N. Thompson. “Corrosion Costs and Preventive Strategies in the United States”, *FHWA Publication No. FHWA-RD -01-156*.
- [2] N. Materer, P. Field, N. Ley, A. Soufiani, D. Scott and T. Ley. (Under Review). “Passive Wireless Detection of Corrosive Salts in Concrete using Wire-Based Triggers” *ASCE Journal of Materials*.
- [3] M. Pour-Ghaz, T. Barret, T. Ley, N. Materer, A. Apblett and J. Weiss (Under Review). “Wireless Crack Detection in Concrete Elements Using Conductive Surface Sensors and Radio Frequency Identification Technology”, *ASCE Journal of Materials in Civil Engineering*.
- [4] ASTM C1543-10, “Standard Test Method for Determining the Penetration of Chloride Ion into Concrete Ponding”.
- [5] ASTM C192/C192M-1a, “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory”.