



### **Sensors for Monitoring Corrosion of Steel Embedded in Concrete**

Udaya B. Halabe

West Virginia University – Department of Civil and Environmental Engineering  
395 Evansdale Drive, Room 613 ESB  
Morgantown, WV 26506-6103  
U.S.A.

Jonas Kavi

West Virginia University – CEE Department  
395 Evansdale Drive, Room B07 ESB  
Morgantown, WV 26506-6103  
U.S.A.

Hota V. S. GangaRao

West Virginia University – CEE Department  
395 Evansdale Drive, Room 653E ESB  
Morgantown, WV 26506-6103  
U.S.A.

### **ABSTRACT**

This paper presents the use of an innovative low cost sensor for monitoring corrosion of steel members embedded in concrete. Corrosion of steel reinforcing bars or embedded steel in concrete structural components is a major concern for structures such as bridges and parking garages. Moisture and chloride ingress through the cracks is the primary reason for corrosion of such concrete structures. The chloride and moisture levels significantly affect the electrical conductivity of concrete. A low cost sensor for measuring concrete resistivity (or conductivity) was developed by researchers at West Virginia University. This sensor is very durable and can be embedded in concrete members (beams, columns, etc.) at the time of pouring concrete. The electrical resistivity measurement obtained using this sensor can be used to evaluate the potential for corrosion of embedded steel. This paper presents laboratory and field results obtained using the sensor to demonstrate its usefulness. The paper also highlights the simplicity and ease of use of this sensor. In addition, the paper also discusses the use of a commercially available temperature/humidity sensor that can be used in conjunction with the electrical resistivity sensor for a comprehensive assessment of the potential for corrosion of steel embedded in concrete.

**Key words:** corrosion, sensor, electrical resistivity, electrical resistance, temperature, humidity, reinforced concrete, fiber reinforced polymer, FRP, composites, NDE, NDT

## INTRODUCTION

Reinforced concrete is one of the most widely used construction materials for infrastructure applications across the world due to its reasonable durability and competitive cost. One of the major concerns with reinforced concrete is the deterioration caused by premature corrosion of embedded steel reinforcement under the influence of moisture, chlorides, and oxygen in the field environment.<sup>1</sup> The need for maintenance and repair of bridges, buildings and other infrastructure for their safety require effective monitoring and evaluation to determine the location and severity/rate of deterioration.

The use of new and advanced materials such as Fiber Reinforced Polymer (FRP) in rehabilitating aging concrete infrastructure (e.g., wrapping of deteriorated concrete members with glass or carbon FRP fabrics) as well as in new construction is on the ascendancy. This is due to FRP having better engineering and desirable properties such as low density, high specific strength and high specific modulus over concrete and steel.<sup>2,3</sup>

Several techniques exist for monitoring corrosion in reinforced concrete. These techniques are primarily based on monitoring of concrete resistivity, corrosion current, moisture content, electric potential, or change in resistance of an embedded element. These techniques were however developed for monitoring corrosion in 'conventional' reinforced concrete structural members, in which the concrete surface is exposed and accessible. The use of FRP shells and/or wraps in rehabilitation and new construction works makes these corrosion monitoring techniques inapplicable to the structures. Furthermore, most of the available corrosion monitoring techniques require the structural member being monitored to be accessible, which makes them unsuitable for use on certain structures (e.g., underwater members). In case of highway bridge members, traffic control is often needed which results in user inconvenience and increased cost.

Therefore, there is a need to develop an alternative corrosion monitoring technique that can be adapted to all forms of reinforced concrete structures (both accessible and inaccessible components of structures, including conventional reinforced concrete structures and those incorporating FRP products). In this study, a low cost and durable corrosion sensor for embedding inside concrete has been developed. These sensors incorporate electrical resistivity measurements. In addition, commercially available temperature/humidity sensor was also embedded inside concrete. The electrical resistivity and moisture content/humidity data were used to develop a methodology for assessing the potential for corrosion of steel encased in concrete structural members. It is important to note that these sensors are made of the same materials that reinforced concrete is made up of, concrete and steel, and therefore do not introduce any weak points in the structure. The sensors are in the form of concrete cubes cured in the laboratory before taking them to the field. Finally, the sensors can be installed in the field during construction/rehabilitation work and the wires from the sensors are brought outside to a central monitoring board, so that access to the structural members is not required for data collection.

## CORROSION MONITORING TECHNIQUES

Structural maintenance can only be carried out appropriately with adequate monitoring and measurement of deterioration. Structural monitoring ensures that sufficient data is obtained on the location and severity/rate of deterioration, hence enabling the right maintenance activity to be carried out on the structure at the right location and at the time when it is most efficient. Thus corrosion monitoring results in lower maintenance costs and "also helps to develop durability models and related predictive techniques to enhance the understanding of macrocell corrosion environments".<sup>4</sup>

Several methods are available for corrosion monitoring, most of which rely on the electrochemical nature of corrosion. Some of the commonly used methods are discussed below.

## Half-Cell Potential (HCP) Method

The principles of an active electrochemical corrosion create a potential difference across the surface of reinforced concrete. This potential can be measured with a standard reference electrode such as copper-copper sulfate electrode (CSE), and the readings give the likelihood of an active corrosion. The apparatus consists of a copper rod immersed in a saturated copper sulfate solution (copper-copper sulfate half-cell), connecting wires and a high impedance voltmeter to take the readings<sup>5</sup>. The test is standardized by ASTM C 876, "Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete". "The half-cell potential readings (at any point on the concrete surface) are indicative of the probability of corrosion activity of the reinforcing steel located beneath the copper-copper sulfate reference cell".<sup>5</sup> As per ASTM C 876, a voltmeter reading which is more negative than -350 mV indicates greater than 90% probability of active corrosion.<sup>6</sup> This voltage is referenced to the copper-copper sulfate reference electrode.

One major limitation of the HCP method is that it requires access to the reinforcing steel and the concrete surface for scanning operations. This can be problematic at times on certain structures.<sup>7</sup>

## Concrete Resistivity Method

The availability of oxygen and moisture are two major factors that control the corrosion rate in steel. The availability of moisture affects electrical resistance of the concrete, which controls the rate at which ions move between the anode and cathode of a corrosion cell through the concrete and hence the rate of corrosion. Concrete with high electrical resistivity has a slower corrosion rate as compared to concrete with low resistivity in which current can flow between the anode and cathode with ease.<sup>1</sup> The most common method of measuring concrete resistivity is by using the Wenner probe. The device consists of four equally spaced, collinear probes that should be connected to the concrete electrically. Researchers have come up with guidelines for interpreting concrete electrical resistivity data, and two such guides are provided in Table 1 below.

**Table 1: A<sup>8</sup> and B<sup>9</sup>) Guides to concrete resistivity data interpretation**

A	Resistivity, k $\Omega$ .m	Corrosion Risk
	$\rho > 0.12$	Corrosion is unlikely
	$\rho = 0.05$ to 0.12	Corrosion is possible
	$\rho < 0.05$	Corrosion is certain
B	Resistivity, k $\Omega$ .m	Corrosion Risk
	$\rho > 0.20$	Low corrosion rate
	$\rho = 0.10$ to 0.20	Low to moderate corrosion rate
	$\rho = 0.05$ to 0.10	High corrosion rate
	$\rho < 0.05$	Very high corrosion rate

This method also requires access to the concrete surface for scanning operations. In addition, the measured resistivity value is affected by the electrical resistivity of the material close to the concrete surface.

## Linear Polarization Resistance (LPR) Method

Unlike the half-cell potential measurement which only gives the probability of active corrosion, this method provides instantaneous corrosion rate of steel reinforcement in the form of corrosion density

( $i_{corr}$ ). It thus enables a more detailed structural condition assessment to be carried out. The most conventional method for measuring the polarization resistance of reinforcing steel in concrete is by the three electrode system, often referred to as the 3LP device. It is however difficult to determine the exact area of reinforcing steel that is affected by the current and a modified version of the device with a fourth (guard) electrode has been developed. The guard electrode is used to regulate and confine the applied current to a known path. This ensures a more accurate determination of affected steel area, which is located approximately under the counter electrode.<sup>5</sup> The following guidelines (Table 2) have been developed for corrosion density data interpretation.

**Table 2: Corrosion density interpretation guidelines for A) device with guard electrode<sup>10,11</sup> and B) device with no guard electrode<sup>12</sup>**

A	Corrosion Current Density ( $i_{corr}$ ), $\mu\text{A}/\text{cm}^2$	Corrosion Risk
	< 0.1	Negligible
	0.1 to 0.5	Low
	0.5 to 1	Moderate
	> 1	High

B	Corrosion Current Density ( $i_{corr}$ ), $\mu\text{A}/\text{cm}^2$	Corrosion Risk
	< 0.2	No corrosion damage expected
	0.2 to 1.0	Corrosion damage possible in 10-15 years
	1.0 to 10	Corrosion damage expected in 2-10 years
	> 10	Corrosion damage expected in < 2 years

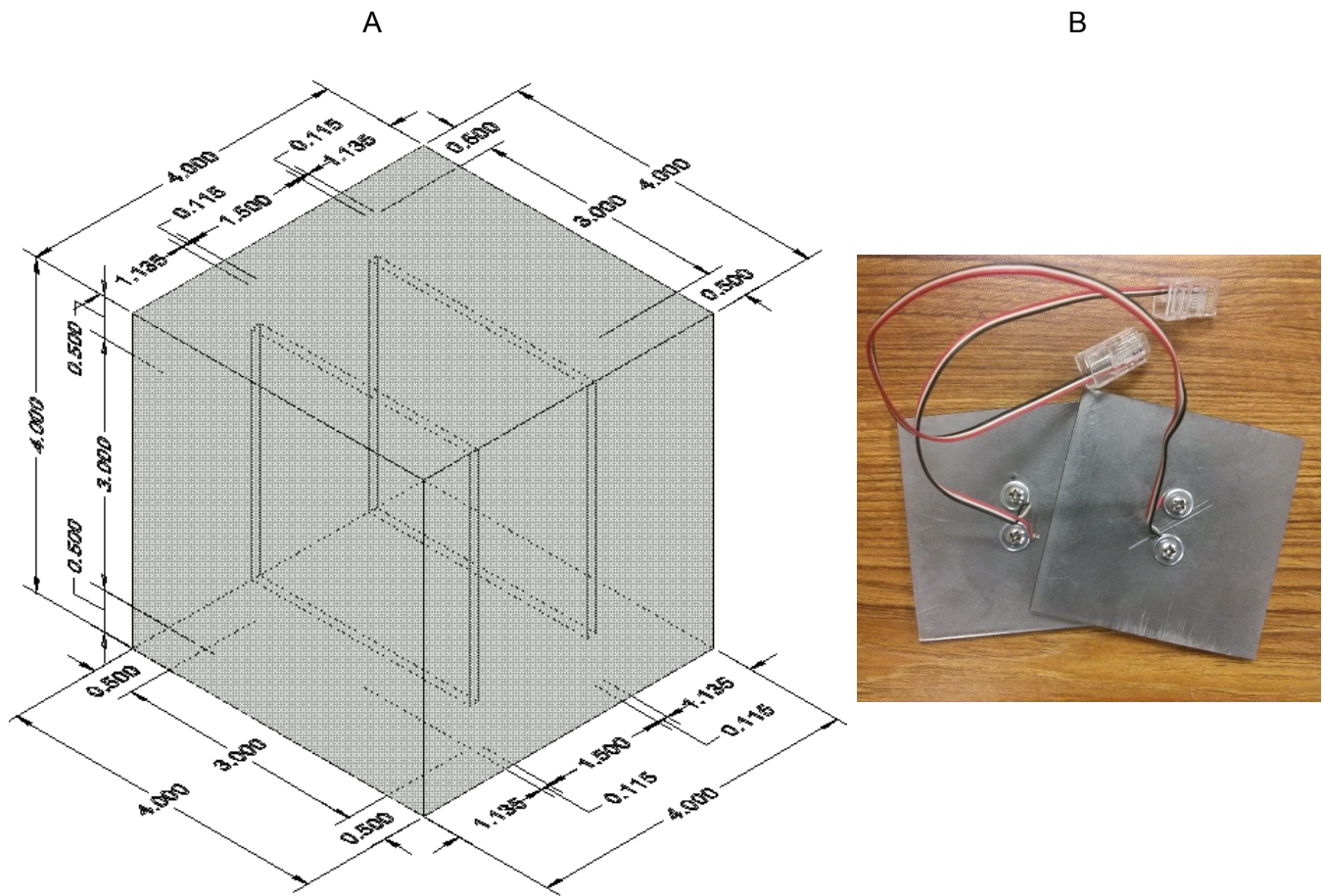
Like the other corrosion monitoring techniques discussed, linear polarization resistance measurement also requires access to the reinforced concrete and the rebar, which is not feasible in certain situations. Most of the available corrosion monitoring techniques are also not applicable for monitoring corrosion of structural members wrapped with FRP fabrics. Hence this study focuses on use of new types of embedded sensors as explained in the next section. These sensors are low cost, do not require access to the structure, and can be used on reinforced concrete structures with and without FRP wraps.

## EXPERIMENTAL PROCEDURE

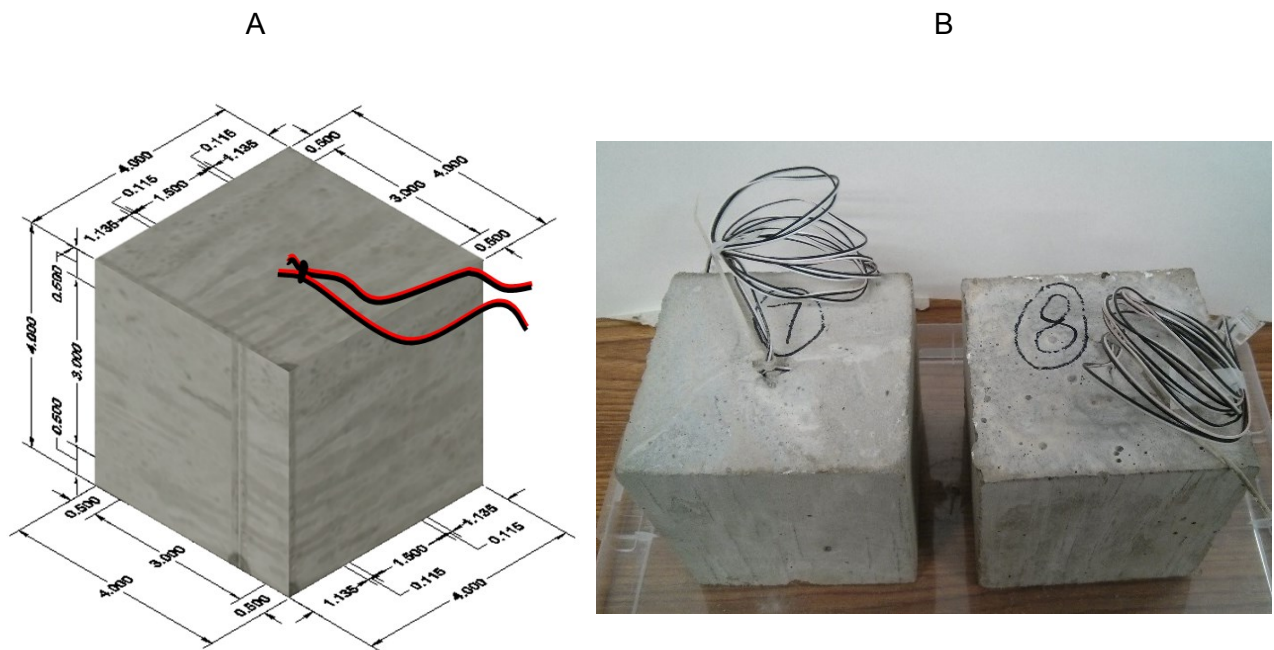
The electrical resistivity sensor developed in this study comprises of two parallel plain carbon (A36) steel plates embedded within a 4"x4"x4" (101.60x101.60x101.60mm) concrete cube. The steel plates were spaced at 1.50" (38.10mm). The size of the concrete cube ensures concrete cover of 1.135" (28.83mm) is provided on both sides of the steel plate assembly and 0.50" (12.70mm) of concrete cover on the other four sides perpendicular to the plate thickness. The cubes were produced using fast-setting concrete mix with a 28 day strength of 31MPa (4500psi). Aggregates in the mix were measured and found to have sizes between 9mm and 14mm. The steel plates used were 3"x3" (76.20x76.20mm) with 0.115" (2.92mm) thickness. The geometry of the designed sensor is shown in Figure 1: A. The sensor also had electrical wires connecting to the plates for resistance measurements as shown in Figure 1: B. A model of the sensor, and a picture of the sensors produced in the lab is shown in Figure 2 (patent application is in progress).

A preliminary design was done in which plain carbon (A36) steel and stainless steel plates were evaluated and found to produce similar results.<sup>7</sup> This is because the sensor measures the electrical resistance of concrete between the plates, and the electrical resistance of the plate itself is negligible compared to that of concrete. Thus stainless steel plates can be used for applications in high corrosive environments where the sensor is required to last for the life of the structural component.





**Figure 1: A) Electrical resistivity sensor geometry showing embedded steel plates (dimensions in inches) and B) steel plates showing connecting wires**



**Figure 2: A) Model of the electrical resistivity sensor (dimensions in inches) and B) actual sensors for laboratory testing**

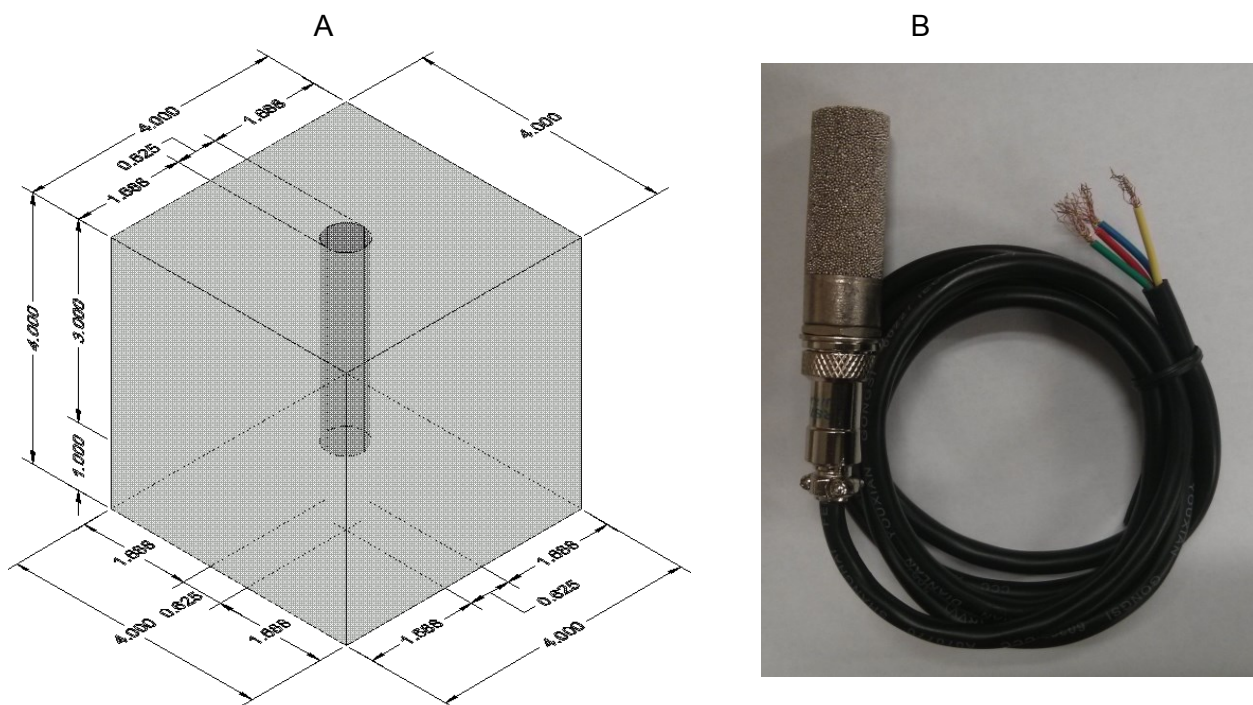
In addition to the electrical resistivity sensor, a commercially available temperature/humidity sensor was also installed to monitor these factors (especially humidity) since humidity level has a direct effect on the concrete resistance and corrosion of steel encased in concrete. In addition, the humidity data will help determine whether lower resistance values observed are primarily due to higher moisture content of the concrete or due to corrosion activity (especially those caused by chloride infiltration). This will result in a better prediction of the potential for corrosion of steel encased in concrete.

The temperature/humidity sensor system was produced by installing commercially available sensor in pre-cured 4"x4"x4" (101.60x101.60x101.60mm) concrete cube with 5/8" (15.875mm) diameter and 3" (76.20mm) deep hole at the top with 1" (25.40mm) concrete cover at the bottom (Figure 3: A). The sensor is shown in Figure 3: B.

The sensor was installed in the cube along with a plastic tube (on the top portion of the hole) to bring the wire out. The area around the wire (inside the plastic tube) was sealed up to prevent water and wet concrete from entering the hole through the opening. This ensures that moisture only gets to the sensor through the concrete pores and prevents the sensors from being damaged by wet concrete when installed in the field during construction or rehabilitation. Figure 4: A shows the completed sensor assembly.

### Laboratory Calibrations

Data was collected from two electrical resistivity sensors, R1 and R2, and one temperature/humidity sensor, T-H1, in the laboratory to develop calibration curves for data interpretation. The sensors (R1, R2, and T-H1) were soaked to ensure that the pores of the concrete became saturated with water (Figure 4: B). The sensors were removed from the water tub after two weeks for laboratory monitoring. Weight and resistance measurements were carried out on the electrical resistivity sensors (R1 and R2) to determine daily variations of these parameters as the sensor concrete dried under laboratory temperature. Data collection on the samples was done continuously for 368 days and 365 days for R1 and R2 respectively. The collected data was then analyzed to generate baseline values and calibration curve for corrosion data interpretation as discussed below.



**Figure 3: A) Geometry of cube for temperature/humidity sensor (dimensions in inches) and B) Temperature/Humidity sensor**



**Figure 4: A) Final temperature/humidity sensor assembly and B) soaked sensors**

Electrical resistivity and moisture content of concrete were computed from the collected data using Equations (1) and (2).

$$\rho = R \frac{A}{L} = 0.1524R \text{ (k}\Omega\cdot\text{m)} \quad (1)$$

Where;

$\rho$  = electrical resistivity, k $\Omega$ .m

$R$  = electrical resistance of a uniform specimen of the material, k $\Omega$

$A$  = cross-sectional area of the material (76.20x76.20mm = 0.00581m<sup>2</sup>)

$L$  = length of the material (plate spacing = 38.10mm = 0.0381m)

$$w = W \left( \frac{1 + w_{Lab \text{ dry}}}{W_{Lab \text{ dry}}} \right) - 1 \quad (2)$$

Where;

$w$  = moisture content of the concrete at each data point

$W$  = weight of concrete at each data point, g

$w_{Lab \text{ dry}}$  = moisture content of the concrete at lab dry condition

$W_{Lab \text{ dry}}$  = weight of lab dry concrete, g

$W_{Lab \text{ dry}}$  was obtained using a controlled sample in the laboratory using oven dry method.

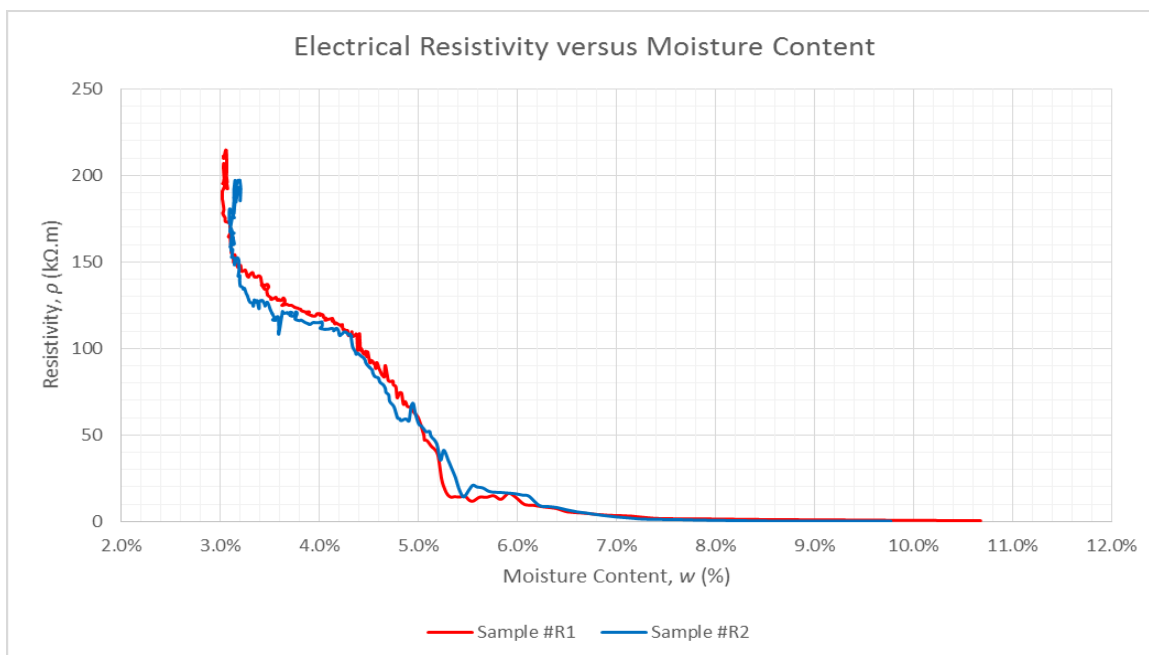
The variation of electrical resistivity values for the two sensors were observed to be consistent with each other over the course of one year.<sup>7</sup> The variation of concrete electrical resistivity with moisture content is shown in Figure 5.

Figure 5 shows two distinct regions, a low electrical resistivity region with a low slope above 5.5% moisture content and a high electrical resistivity region with a significantly higher slope below 5.5% moisture content. In the latter region, the connectivity between water molecules in the concrete pores is lost, thus leading to a steep electrical resistivity curve.

As seen from Table 1: B, corrosion activity is only likely if the resistivity of the concrete goes below 0.2k $\Omega$ .m. This means corrosion activity was unlikely in the two cubes during the course of the study since the resistivity value never dropped below the 0.2k $\Omega$ .m threshold. This is because the samples

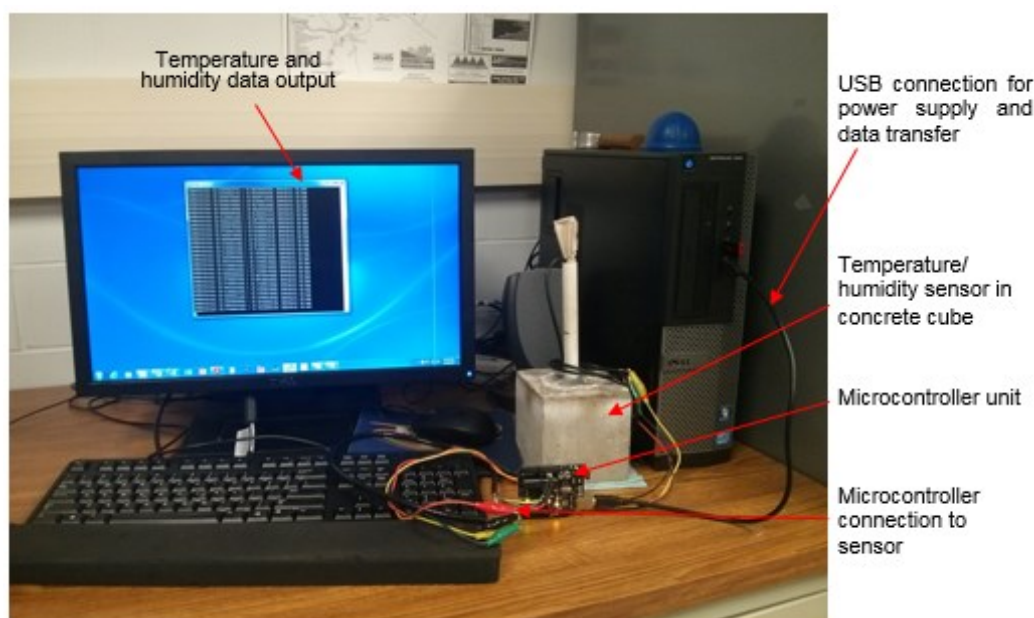


were new and had not been exposed to carbonation or chlorides in the field. Some researchers have questioned the 0.2kΩ.m threshold and have suggested that corrosion activity is likely if the resistivity value goes below 1kΩ.m.<sup>7</sup>



**Figure 5: Variation of concrete electrical resistivity with moisture content**

Similar to samples R1 and R2, the sample T-H1 (encasing the temperature/humidity sensor) was also soaked in water for two weeks and then allowed to dry in the laboratory. During the lab drying period, the sensor was monitored for weight, temperature and humidity variations for 368 days. A microcontroller unit was used, along with a computer, for obtaining data from the temperature/humidity sensor (Figure 6).



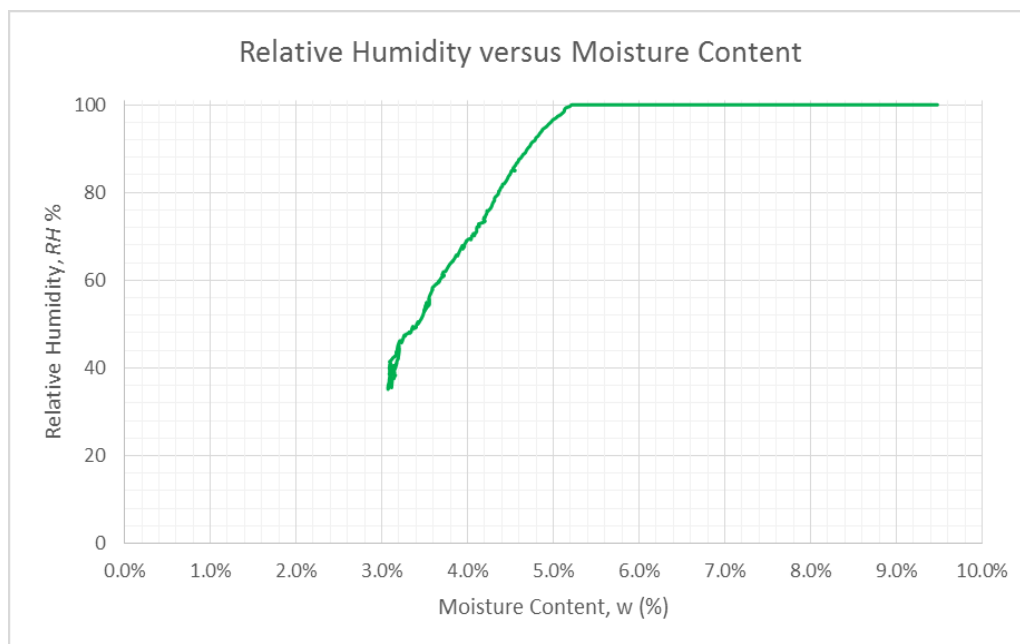
**Figure 6: Data collection set-up for temperature/humidity sensor**



Temperature within the concrete was found to be fairly stable throughout the study period, since the sample was in the laboratory environment. The temperature fluctuation was within the range of 20.7-27.4°C and an average of 23.4°C.

The variation of relative humidity within the sample with moisture content is shown in Figure 7. Equation (2) was used for computing moisture content of the cube.

The relative humidity remained constant at 99.99% level when the concrete was saturated till the moisture content dropped below 5.3%, and then decreased gradually at a constant rate to 3.2% moisture content as shown in Figure 7.



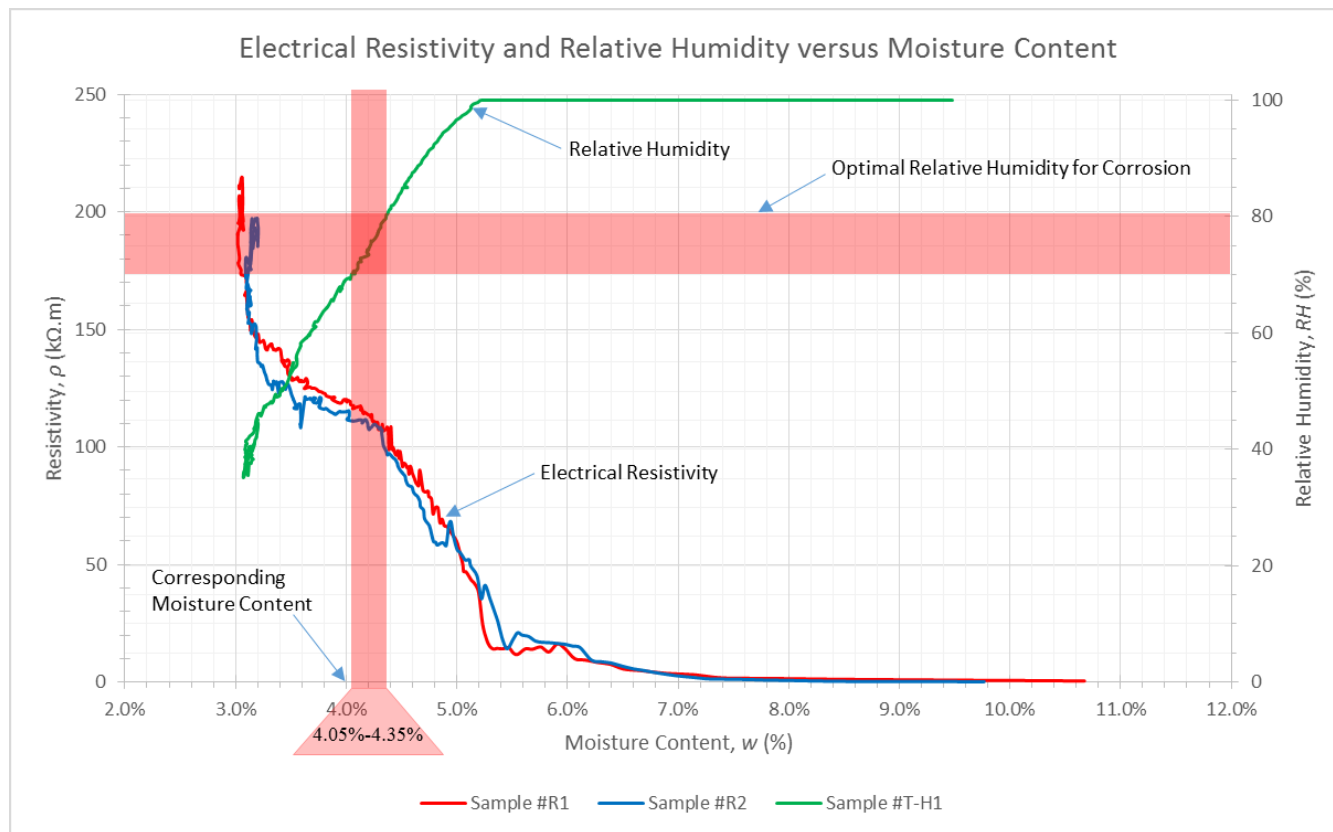
**Figure 7: Variation of relative humidity with moisture content**

Data obtained from the electrical resistivity sensors were combined with the one obtained from the temperature/humidity sensor to develop the calibration curve for field data interpretation. As has been discussed, the probability for corrosion of steel encased in concrete is minimal when the concrete resistivity is above 0.2kΩ.m level. This is because high resistivity of concrete restricts the movement of ions and current through the concrete, thereby limiting corrosion.

In addition, the optimal relative humidity for corrosion of reinforced concrete is 70-80% as stated in the published literature.<sup>13</sup> At humidity below 70%, concrete becomes too dry and there is not enough moisture for the reduction reaction and ionic movement through the concrete, hence dry concrete does not corrode. Also, at humidity above 80%, concrete is close to saturation and there is not enough oxygen for the reduction reaction to proceed and hence no corrosion takes place. The latter point is reinforced with Figure 9: B (under Field Testing Results and Interpretation), where portions of the steel H-piles permanently under water showed no corrosion after decades of service in the field environment. The relative humidity range of 70-80% was found to correspond with moisture content of 4.05-4.35% for the T-H1 sensor tested in the laboratory.

The likelihood of corrosion is very high when the relative humidity is between 70-80% and the concrete resistivity is below 0.2kΩ.m but minimal for all other conditions. The likelihood of corrosion is much lower when the relative humidity and concrete resistivity values are away from the optimal ranges. The above observations are shown in Figure 8.

Thus, there is a high potential for corrosion of the embedded steel if low resistivity values below  $0.2\text{k}\Omega\cdot\text{m}$  is observed at the time when the relative humidity within the concrete is between 70-80% (moisture content of the concrete is around 4%). Infiltration of chlorides into concrete can significantly lower the electrical resistivity value of concrete and increase the potential for corrosion of the embedded steel.



**Figure 8: Calibration curve for corrosion data interpretation**

## FIELD TESTING RESULTS AND INTERPRETATION

Six electrical resistivity sensors and eight temperature/humidity sensors were installed to monitor the newly rehabilitated columns of USACE East Lynn Lake Bridge in West Virginia. The sensors were installed during the rehabilitation work conducted in March 2014.

East Lynn Lake Bridge was constructed during 1971-72. The bridge is 126.5 feet long and comprises of 2 lanes, 5 spans of continuous reinforced concrete slab supported by steel H-piles and abutments.

Figure 9: A shows the bridge prior to the rehabilitation work. The portion of the steel H-piles above the permanent water level got corroded over time due to seasonal rise and fall in the water levels, resulting in section loss of the steel up to 50%. The capacity of the bridge was thus reduced, resulting in load rating of 6 tons (the original rating was around 15 tons), with one lane closure and maximum speed reduced to 10 mph.<sup>14</sup>

The portion of the steel H-piles above the fluctuating water level was free of corrosion damage. This can be attributed to the fact that even though that portion of the H-pile may have gotten wet, the moisture was not enough to cause corrosion. In addition, that portion of the pile can act as the cathode for corrosion reactions and hence not suffer corrosion damage.

The portion of the steel H-piles about 1 foot below the ground surface was sound and free from corrosion (Figure 9: B). This was observed after 3 feet deep trenches were dug around the piles to expose the portion beneath the ground surface. This portion of the piles did not corrode because it was permanently submerged under water and there was no oxygen available to promote corrosion reaction.



**Figure 9: A) East Lynn Lake Bridge before rehabilitation and B) submerged portion of piles free from corrosion damage**

The bridge piles were rehabilitated by encasing them in self-consolidated concrete (SCC) wrapped with advanced FRP composite materials to bring the bridge back to its original design capacity. During the rehabilitation process, polymer concrete was used as a foundation barrier, which also took the load of the SCC above it. The FRP jackets/shells served as formwork for pouring SCC and also enhanced the load carrying capacity of the rehabilitated columns by providing confinement. The polymer concrete also serves to prevent the lake water from getting to the concrete above it after the rehabilitation.

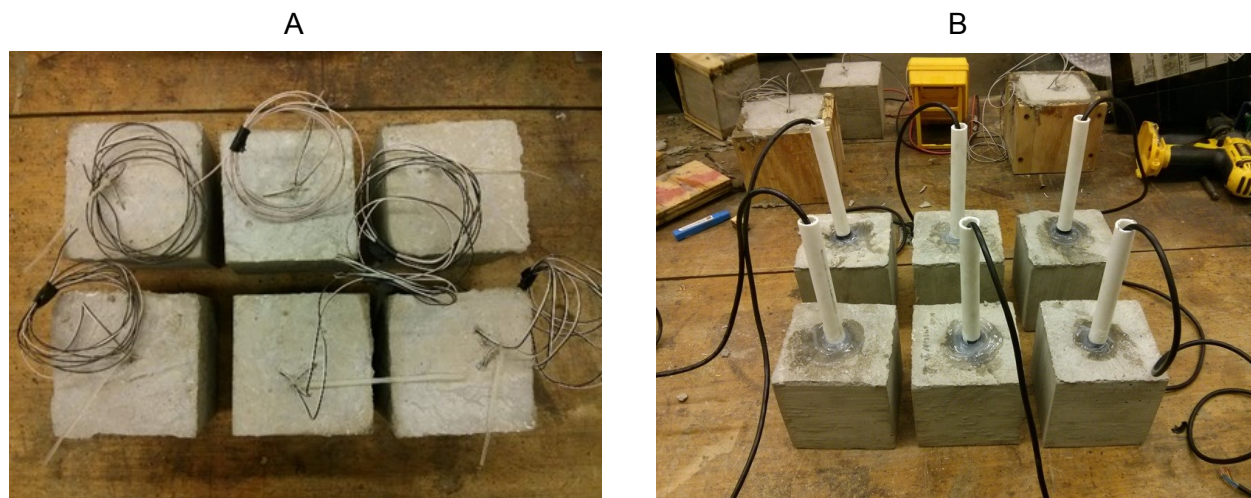
The steel H-piles were enclosed in 20" diameter glass fiber reinforced polymer (GFRP) composite shells. The GFRP shells surrounding the steel H-piles were then wrapped with two layers of GFRP fabric and filled with self-consolidated concrete. The self-consolidated concrete had a 28 days strength of 21MPa (3050psi).<sup>14</sup> Finally, UV protective coating was applied to the surface of the completed columns (surface of GFRP wraps). The GFRP wrap also provided a water-tight seal, preventing the lake water from entering the rehabilitated piles.

Before the FRP shells were installed, six electrical resistivity sensors and six temperature/humidity sensors (Figure 10) were attached to the surface of the steel piles (in the corroded portion) to enable nondestructive monitoring of further corrosion potential after rehabilitation. Two sensors of each type were attached to three steel piles. In addition, two temperature/humidity sensors were placed outside in a location under the bridge to measure the ambient temperature/humidity. The sensors were wired and connected to a central monitoring board, which can house a data acquisition unit if needed. Figure 11: A shows the sensors attached to a steel pile. The rehabilitation of the 20 piles (columns) of the bridge was completed in 3 weeks during March 2014, which brought the bridge back to the original design capacity at 25% of conventional construction cost for the bridge.<sup>14</sup> Figure 11: B shows the bridge after rehabilitation, together with the pile identification labels used for data interpretation.

The sensors were installed in three of the piles (Pile 3 in Bent 1, and Piles 3 and 4 in Bent 2). The three piles had two sensors of each type (electrical resistivity, and temperature/humidity), placed in the



corroded portion. Also, two temperature/humidity sensors were placed outside in a location under the bridge to measure the ambient temperature/humidity.



**Figure 10: A) Electrical resistivity sensors and B) temperature/humidity sensors**



**Figure 11: A) Electrical resistivity and temperature/humidity sensors installed in the field and B) East Lynn Lake Bridge after rehabilitation, showing pile identification labels**

## Field Testing Results

After rehabilitation, electrical resistivity and temperature/humidity data was collected from the bridge piles (columns) to monitor them for further corrosion. Two field trips were made to collect data from the embedded sensors in the bridge during a six months interval. Table 3 presents the data obtained during these trips. Equation (1) was used in computing the resistivity values in Table 3.

The high relative humidity value of 99.99% (for the embedded temperature/humidity sensors 1 through 6) in Table 3 means the concrete is saturated and the potential for corrosion of encased steel is very low since no oxygen will be available within the concrete to promote corrosion. The high humidity within the concrete also means there will be no shrinkage cracks developed in the concrete. It should be noted that this high humidity is not due to moisture ingress from the lake. This humidity resulted from the excess water left after curing of the self-consolidated concrete that is trapped within the concrete piles by the polymer concrete foundation barrier and the GFRP shell and wraps surrounding the piles.



**Table 3: Field data for East Lynn Lake Bridge**

**Electrical Resistivity Measurement**

Sensor	Location	Resistance (k $\Omega$ )		Resistivity (k $\Omega$ .m)			
		06/10/14	12/10/14	06/10/14	12/10/14		
Resistivity 1	Bent 2 Pile 3	26.7	27.8	4.1	4.2		
Resistivity 2	Bent 2 Pile 3	28.7	39.0	4.4	5.9		
Resistivity 3	Bent 2 Pile 4	4.8	-	0.7	-		
Resistivity 4	Bent 2 Pile 4	3.8	17.7	0.6	2.7		
Resistivity 5	Bent 1 Pile 3	67.5	28.9	10.3	4.4		
Resistivity 6	Bent 1 Pile 3	78.7	15.0	12.0	2.3		

**Temperature/Humidity Measurement**

Sensor	Location	June 10, 2014			December 10, 2014		
		Temp. °C	Temp. °F	Humidity %	Temp. °C	Temp. °F	Humidity %
Temperature/Humidity 1	Bent 2 Pile 3	25.60	78.20	99.99	4.95	41.00	99.99
Temperature/Humidity 2	Bent 2 Pile 3	25.40	77.80	99.99	4.88	40.89	99.99
Temperature/Humidity 3	Bent 2 Pile 4	25.40	77.90	99.99	4.75	40.67	99.99
Temperature/Humidity 4	Bent 2 Pile 4	25.50	78.10	99.99	5.02	41.10	99.99
Temperature/Humidity 5	Bent 1 Pile 3	24.90	77.20	99.99	5.00	41.07	99.99
Temperature/Humidity 6	Bent 1 Pile 3	25.40	77.70	99.99	5.16	41.39	99.99
Temperature/Humidity 7	Bent 1*	23.80	75.10	75.40	3.87	39.05	73.76
Temperature/Humidity 8	Bent 2**	22.50	72.70	83.40	3.90	39.09	72.67

External

External

**External**

External sensors, located outside the piles

\* Sensor located at edge of Bent 1

\*\* Sensor located at center of Bent 2

Relative humidity outside the piles was found to be between 72.67% and 83.40% for the two data sets collected, which indicates that the environment is moist during both summer and winter months.

Electrical resistivity values of the piles, presented in Table 3, were found to be higher than the 0.2k $\Omega$ .m threshold value even though the concrete is saturated. This high resistivity value means movement of ions through the concrete will be restricted, thereby preventing corrosion. It is also important to note that the FRP shells and wraps will prevent the salt water from the lake to infiltrate into the concrete piles. This further emphasizes the point made earlier that the potential for corrosion of the encased steel H-piles is very low.

The data obtained from field monitoring of East Lynn Lake Bridge shows the suitability of the newly designed electrical resistivity sensor and the commercially available temperature/humidity sensor for monitoring the potential for corrosion in reinforced concrete structures. It also shows these sensors can be used in monitoring buried and submerged structures, as well as reinforced concrete structures wrapped with FRP shells and/or fabric wraps. The sensors also show that the polymer concrete foundation barrier, and the GFRP shell and wraps have made the piles water tight, protecting them from the surrounding lake water, and significantly reducing the potential for corrosion of the encased steel H piles.

## CONCLUSIONS

A low cost and durable corrosion monitoring technique has been developed in this research using electrical resistivity and temperature/humidity measurements. The following conclusions can be made from the findings of this research:

1. The literature review has shown that corrosion of steel in concrete is most likely to occur if the concrete resistivity is less than 0.2k $\Omega$ .m and when the relative humidity within the concrete is between 70-80% (which corresponds to moisture content of around 4% for the electrical resistivity sensors developed in this study).
2. For concrete resistivity below 0.2k $\Omega$ .m, if the relative humidity within the concrete is higher than 80%, corrosion is less likely since the concrete becomes close to saturation at that humidity level and very little oxygen will be available to promote corrosion.
3. Higher resistivity of concrete limits the flow of ions through the concrete, thereby making it less likely for corrosion to occur.
4. As relative humidity within the concrete gets below 70%, corrosion of steel becomes less likely since there will be not enough moisture to promote reduction reactions and ionic transport.
5. The electrical resistivity and temperature/humidity sensors investigated in this research offer a low cost system for field monitoring of potential for corrosion of steel encased in concrete structural members, with or without FRP wraps.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by the U.S. Army Corps of Engineers (USACE) under Contract No. IIP-1230351 that enabled them to undertake this research.

## REFERENCES

1. H. W. Song, V. Saraswathy, "Corrosion Monitoring of Reinforced Concrete Structures - A Review," *International Journal of Electrochemical Science*, 2 (2007): p. 1-28.
2. H. V. S. GangaRao, N. Taly, P. V. Vijay, *Reinforced Concrete Design with FPP Composites*. (London: CRC Press, 2007).

3. P. K. Mallick, *Fiber-Reinforced Composites: Materials, Manufacturing and Design*, 3rd ed. (London: CRC Press, 2007).
4. L. Xing, D. Darwin, J. Browning, "Evaluation of Multiple Corrosion Protection Systems and Corrosion Inhibitors for Reinforced Concrete Bridge Decks," (A Report on Research Sponsored by Federal Highway Administration, Kansas Department of Transportation, 2010).
5. N. J. Carino, "Methods to Evaluate Corrosion of Reinforcement," in *Handbook on Nondestructive Testing of Concrete*, 2nd ed., V. M. Malhotra and N. J. Carino, Eds. (Boca Raton, FL: CRC Press, 2004).
6. ASTM C 876 (latest revision), "Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete" (West Conshohocken, PA: ASTM International, 2009).
7. J. Kavi, "Nondestructive Evaluation of Corrosion in Reinforced Concrete Structures with or without FRP Wraps," (M.S. Thesis, Department of Civil and Environmental Engineering, West Virginia University, Morgantown, WV, U.S.A., 2015).
8. D. G. Manning, "Detecting Defects and Deterioration in Highway Structures," 1985. (National Cooperative Highway Research Program Synthesis of Highway Practice 118).
9. J. H. Bungey, S. G. Millard, *Testing of Concrete in Structures*, 3rd ed. (New York: Chapman & Hall, 1996).
10. C. Andrade, C. Alonso, "Corrosion rate monitoring in the laboratory and on-site," *Construction and Building Materials* 10, 5, (1996): p. 315-328.
11. A. Feliú, J. A. González, C. Andrade, "Electrochemical methods for on-site determinations of corrosion rates of rebars," *Techniques to Assess the Corrosion Activity of Steel Reinforced Concrete Structures*, ASTM STP 1276, (1996).
12. K. C. Clear, "Measuring Rate of Corrosion of Steel in Field Concrete Structures," *Transportation Research Record* 1211, (1989): p. 28-37.
13. E. Bastidas-Arteaga and M. G. Stewart, "Probabilistic cost-benefit analysis of climate change adaptation strategies for new RC structures exposed to chloride ingress," (Safety, Reliability, Risk and Life-Cycle Performance of Structures and Infrastructures, London, 2013).
14. R. Liang, M. Skidmore, H. GangaRao, "Rehabilitation of East Lynn Lake Bridge Steel Pile Bents with Composites," Presentation at TRB Innovative Technologies for a Resilient Marine Transportation System 3rd Biennial Research and Development Conference (Washington, DC, June 24-26, 2014).