Correlation of Chloride Diffusivity and Electrical Resistivity for Cracked Concrete

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Abstract*– The Durability of Reinforced Concrete (RC) Structures in the Marine environment is causing increasingly serious concerns in the structural infrastructure. RC structures, exposed to aggressive environments, are expected to last with little or no maintenance for long periods of time. However, one of the most serious environmental exposures that cause degradation is Chloride Diffusion, with tide-simulated wet and dry conditions at the air-water interface. In this investigation, a joint project with Cemex (a cement mixing company), the objective is the experimental investigation of the correlation of Chloride Diffusivity with Electrical Current Resistivity of Sound and Macro Cracked Concrete. The principal benefit of the research is the formulation of models to predict the time-dependent Chloride Penetration into Sound and Cracked Concrete in the Marine Environment.

***Keywords--* Corrosion, Concrete, Diffusivity, Resistivity, Permeability, Marine Environment**

I. INTRODUCTION

All over the world, large concrete structures, such as bridges, high rise residential buildings, and harbors, are exposed to severe marine and coastal environments. This type of environment decreases the durability by increasing the inevitable corrosion of the reinforcing steel. For a designer, corrosion is one of the main important concerns when designing a structure, which will experience its lifetime within a marine environment. Durability of reinforced concrete is considered a huge problem, because of the large expense in constructing and maintaining these structures.

One of the many concerns in concrete durability is corrosion due to chloride penetration into the reinforced concrete. Once chloride ions have penetrated through the concrete, the steel surface can oxidize, cracking the concrete due to the corrosion-induced volume expansion of the steel, compromising the bond that exists between the concrete and steel reinforcement, which can cause failure. Thus, chloride penetration turns out to be an appropriate measure of durability.

The objective of this research project was to evaluate the correlation of Surface Resistivity and Rapid Chloride Penetration and enable a quick measure of resistivity to predict Chloride Diffusivity of Cracked concrete.

II. BACKGROUND

Capillary absorption, hydrostatic pressure, and diffusion are the means by which chloride ions can penetrate concrete [1].

When a concrete is exposed to the marine environment, it will undergo wetting and drying cycles in the splash zone, causing build-up of the chloride on the rebar, and consequent corrosion-induced cracking. Due to the load on the structure, and the chemical attack, cracks continue to expand and cause spalling of the concrete surface layer, which aggravates the corrosion of steel, reduces the durability, and even causes failure of the structure.

Corrosion of steel in concrete is an electrochemical process which depends mainly on electrical resistivity of the material, and diffusion of chlorides and oxygen into the concrete [2]. The most common process inducing corrosion is diffusion, the movement of chloride caused by concentration gradients, within the pore solution of the concrete [1].

A. *Chloride Diffusion*

Diffusion of chloride ions in saturated concrete under steady-state conditions is assumed to be governed by the one-dimensional Fick's First Law below, although it is really a three-dimensional process:

$$J = -D_{eff} \frac{dC}{dx}, \tag{1}$$

where

J = flux of chloride ions ($\mathrm{mol/m^2/s}$)
D_{eff} = diffusion coefficient ($\mathrm{m^2/s}$)
C = chloride ions concentration at distance x ($\mathrm{mol/m^3}$)
x = position with respect to surface of concrete (m)

This equation governs the chloride diffusing through the porous cement matrix and the pore solution contained within.

However, for non-steady conditions (when concentrations are changing) diffusion of chloride ions into concrete generally obeys Fick's Second Law of Diffusion given below.

$$\frac{\partial C}{\partial t} = D_{eff} \frac{\partial^2 C}{\partial x^2} \tag{2}$$

Given the boundary conditions of

$$C_{(x+0,t>0)} = C_0, C_{(x>,t=0)} = 0, \text{and}\, C_{(x+\infty,t>0)} = 0,$$

the solution to this differential solution is as follows:

$$\frac{C(x,t)}{C_0} = 1 - e_{rf} \cdot \frac{x}{\sqrt{4D_{eff}t}}, \tag{3}$$

where

C_0 =Surface Concentration (mol/m^3)

$C(x,t)$ = concentration at depth x at time t (mol/m^3)

erf = Error Function

t = time (s)

Fick's Law describes the rate at which a particle diffuses at a given temperature. Higher the temperature, the higher is the diffusion rate, which can be described by the Arrhenius Equation given below.

$$D = D_0 e^{-\frac{E_A}{RT}}, \tag{4}$$

where

D = Diffusion coefficient (m^2/s)

D_0 = Maximum diffusion coefficient at infinite temperature (m^2/s)

R = Universal gas constant ($8.314\ J/mol \cdot K$)

E_A = Activation energy ($J/mole$)

T = Temperature (K)

Equation (2) has been extended to two-dimensions, and the solution obtained for $C(x,y,t)$ [2].

$$C(x,y,t) = C_0 \left(1 - erf\left(\frac{x}{\sqrt{4Dt}}\right) erf\left(\frac{y}{\sqrt{4Dt}}\right) \right) \tag{5}$$

B. Electrical Resistivity

The measurement of a material's ability to resist the passage of electrical current is called Resistivity. The electrical current is passed by the ions in the pore solution of the concrete cement matrix. It is, therefore, reasonable to assume that the current would follow a similar path as any ion moving in the concrete. Following this assumption, Ohm's law can be used to govern the current flow:

$$V = IR \tag{5}$$

where:

V – electrical potential across the specimen (V)

I – current passed through the sample (A)

R – Resistance of the circuit (Ω)

The resistivity (ρ) is calculated by using the equation below:

$$\rho = R\frac{A}{L} \tag{6}$$

where:

ρ – Resistivity of the concrete (Ω-m)

A – cross-sectional area of specimen (m^2)

L – length of specimen (m)

II. METHODOLOGY

A. Rapid Chloride Penetration (RCP)

For each of two mixes, two sets of two cylindrical specimens (Φ 4 in. × 2 in.), one sound and one cut in each set, were tested for Rapid Chloride Permeability, according to ASTM C1202 Standard [3].

Once the specimens were cured for 28 days, they were tested in the following steps:

1. Two of the four specimens (Φ 4 in. × 2 in.) were cut as shown below in Figure 1.

Figure 1. Sound and cut specimens for RCP testing

2. The specimen sides were covered with epoxy coating, and set aside to dry.
3. Once dried, specimens were placed in a vacuum chamber for 3 hours to remove air and other gases.
4. Deionized water was input into the vacuum chamber to saturate the specimens and fill the voids, previously occupied by the air.
5. The specimens remained in the chamber for 19 hours, to saturate in the deionized water.
6. The specimens were sealed with a sealant and fully covered with an impermeable plastic, and left to dry.
7. Once dried, the specimen was mounted in a RCP testing cell, Figure 2. The test procedure used was to pass an electric current through a concrete disk, sandwiched between 2 alkaline solutions: 3% NaCL and 0.3 NaOH, in hollow cells. The test was performed for 6 hours. Figure 3, adopted from ASTM C1202, shows this test setup.

Figure 2. Specimen mounted between the hollow cells

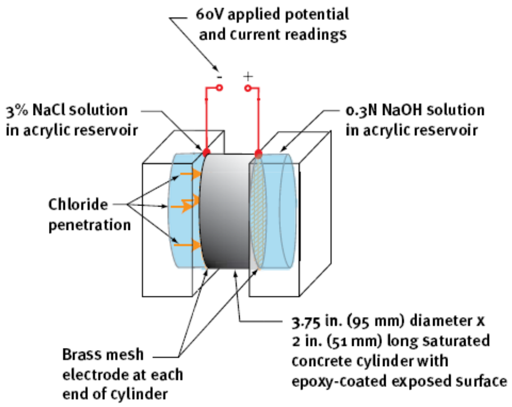

Figure 3. Schematic of rapid chloride permeability test setup for cracked and sound concrete

8. Table 1 was used to determine the Chloride Ion penetration class of the specimen.

Table 1. Chloride Ion Permeability Class of Specimens

Chloride Ion Permeability Class	RCP Test Charge Passed (Coulombs)
High	> 4,000
Moderate	2,000 – 4,000
Low	1,000 – 2,000
Very Low	100 – 1,000
Negligible	< 100

B. *Surface Resistivity (SR)*

Figure 4. Sound and cut specimens for Surface Resistivity Testing

For each of the two mixes, two sets of two cylindrical specimens (Φ 4 in. × 8 in.), one sound and one cracked concrete were tested for resistivity in accordance to the ASTM D257 and AASHTO TP 95 standard methods, using the Wenner Array probe [1]. The equipment needed to perform the SR test included:

1. Wenner 4-point probes with spacing of 1.5" (compliant with the AASHTO Provisional Standard TP 95 on Surface Resistivity), Figure 6.
2. Resistivity Meter

Using the four-probe Wenner test, current (*I*) is measured by the two outside electrodes, which send an electrical current into the concrete. The voltage (*V*) is measured by the two inside electrodes.

Once the specimens were cured for 28 days, they were tested in the following steps:

1. The specimens were marked at 0°, 90°, 180° and 270° locations, in accordance with AASHTO TP 95-11 and ASTM D257, to determine their electrical resistance, Figure 5.

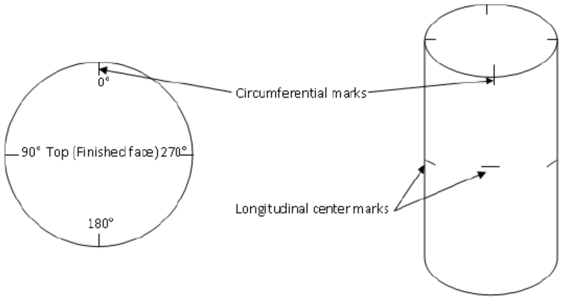

Figure 5. Markings on specimens for resistance testing

2. The specimens were placed horizontally on the apparatus bed, and the wetted four-point Wenner Array Probes were mounted on the concrete (see Figure 6. Schematic for SR test), and its resistance measured for a total of eight times (two at each location).

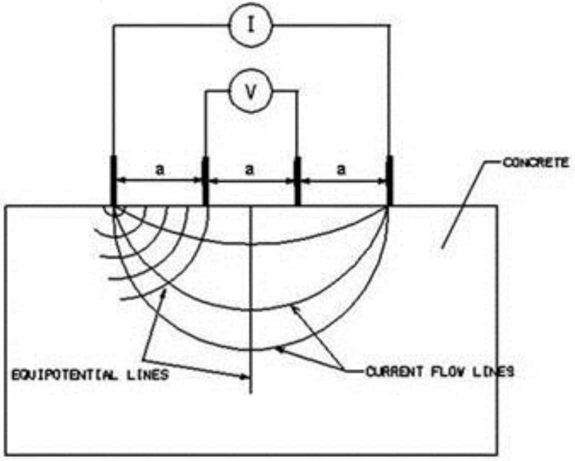

Figure 6. Schematic for SR test

3. The measurements were used to evaluate the permeability class of the concrete using Table 2, adopted from Reference [4].

Table 2. Chloride Ion Penetration Based on Surface Resistivity (4” x 8” Cylinder)

Chloride Ion Permeability Class	4” X 8” Cylinder (KΩ-cm)
High	< 12
Moderate	12 - 21
Low	21 – 37
Very Low	37 – 254
Negligible	> 254

The correlation between diffusivity and surface resistivity for sound concrete has been investigated by Reference [6] and [7]. The chloride diffusivity of concrete with simulated cracks was investigated earlier by Reference [8]. The objective in this study is the correlation between Diffusivity (Coulombs) and Resistivity (Kohm-m) for sound concrete and concrete with simulated cracks cylinders, which are plotted in Figures 7 and 8, which indicates that the relatively simple test of resistivity can be adequate to predict diffusivity.

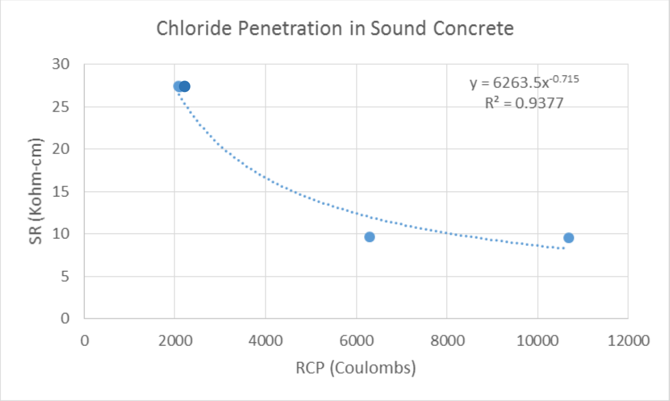

Figure 7. SR vs. RCP for Sound Concrete

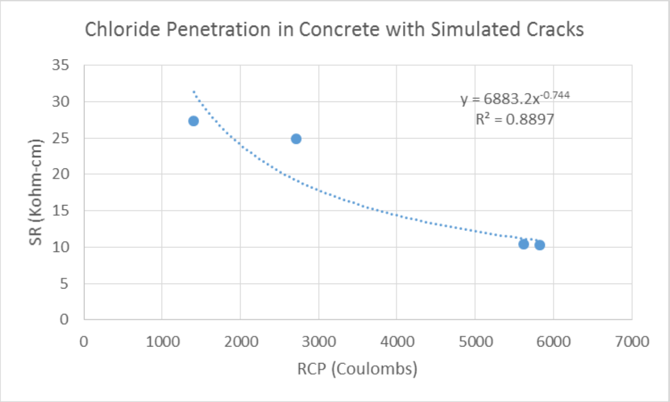

Figure 8. SR vs. RCP for Cracked Concrete

Table 3. RCP vs. SR for Sound and Cracked Concrete

Test	RCP (Coulombs)		SR (Kohm-cm)	
	Mix A$^{\bullet}$	Mix B $^{\bullet\bullet}$	Mix A$^{\bullet}$	Mix B$^{\bullet\bullet}$
Sound Concrete	6,303	2,084	9.7	27.4
	10,681	2,095	9.5	27.3
Cracked Concrete	5,625	1,402	10.4	27.3
	5,826	2,711	10.3	24.9

$$\bullet = f_c^{'}(5000\,psi) \quad \bullet\bullet = f_c^{'}(3500\,psi)$$

III. DISCUSSION

The results need to be compared with those calculated by using Fick’s Second Law, Equation 2. However, this would require more experimental data, which is now being obtained from further testing.

In an investigation by Reference [5], insulating films were embedded at different locations to study the effect of the number and locations of the defects. However, they had little effect on the electrical conductivity of specimens.

IV. CONCLUSIONS

In spite of the small number of results, the correlation between RCP and SR tests seems to indicate that the simple resistivity test is adequate to predict diffusivity of cracked concrete.

Once the testing is completed, this investigation will benefit the concrete and construction industries by providing experimental evidence that the Surface Resistivity test is an effective alternative to the RCP test of measuring chloride penetration for both sound and cracked concrete.

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REFERENCES

[1] K.D. Stanish, R.D. Hooton, and M.D.A. Thomas, “Testing the chloride penetration resistance of concrete: a literature review.” FHWA Federal Highway Administration contract DTFH61, 1997, pp. 19-22.

[2] D.V. Reddy and S. Ranade, “Computer modeling for chloride diffusion and corrosion fatigue of reinforced concrete beams in the marine environment.” ACI Spring Convention, San Francisco, CA, March 20-25, 1994.

[3] ASTM C1202-12, Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, ASTM International, West Conshohocken, PA, 2012.

[4] R.J. Kessler, R.G. Powers, E. Vivas, M.A. Paredes, and Y.P. Virmani, “Surface resistivity as an indicator of concrete chloride penetration resistance.” Concrete Bridge Conference, St. Louis, Missouri, 2008.

[5] Y.Z. Wang, Y.Z. Xu, and Y. Sun, “Experimental study on electrical conductivity of carbon fiber reinforced concrete underwater.” AMR Advanced Materials Research, Trans Tech Publications, Switzerland, 461, 2012, pp. 246–249.

[6] E.W. Ryan, “Comparison of two methods for the assessment of chloride ion penetration in concrete a field study.” Thesis, 2011.

[7] M. Thomas, T. Moffat, Y. Huang, and D.E. Smith, “Electrical methods for estimating the chloride resistance of concrete.” ACI Fall Convention, Phoenix, AZ, October 20-24, 2013.

[8] C. Andrade, and R. D'andrea, “The use of electrical resistivity as a NDT for the specification of concrete durability.” Concrete Under Severe Conditions, Two Volume Set, 195–200, 2010.