SURFACE RESISTIVITY AS AN INDICATOR OF CONCRETE CHLORIDE PENETRATION RESISTANCE

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ABSTRACT

It is common for the durability requirements of concrete structures built today to have a projected minimum service life of 75 years or more. In order to ensure that a new structure achieves such long life, requires the use of high performance concretes made with the latest proven pozzolanic materials.

Concrete chloride penetration resistance of concrete is among the most significant properties used to characterize high performance concretes today. To that effect diffusion tests are used, but because of their long duration, they do not lend themselves to measuring the chloride penetration properties of concrete during the course of construction.

Surface Resistivity (SR) of water-saturated concrete at several different ages was studied and compared to the diffusion properties of the same concrete. A case is made to use SR as an electrical indicator of concrete chloride penetration resistance because of its strong correlation to diffusion tests, ease of implementation, non-destructive nature, and lower cost than any other test available.

Keywords: Surface Resistivity, Corrosion, Concrete, Chloride, Permeability, Pozzolans, Fly Ash, Silica Fume, Metakaolin, Diffusion, Slag, SFFA, Ternary Blend, HPC, Chloride Penetration, BD

INTRODUCTION

In 2002 the Florida Department of Transportation started a research program to evaluate all available electrical indicators of concrete chloride penetration resistance. From the beginning of this program, the FDOT was not looking for a one size fits all test that could be used unmodified for all types of concretes. Instead, the intent was to identify an electrical test that was simple, inexpensive, nondestructive, strongly correlated to diffusion, with low coefficient of variation, and that could easily be modified to test new concrete formulations.

The first project[1] under the research program had the simple purpose of investigating if it was possible to replace the labor intensive, time consuming Rapid Chloride Permeability (RCP[2,3]) test (AASHTO T277, ASTM C1202, Fig. 1) by the simple non-destructive Surface Resistivity (SR) test (FM5-578[4], Fig. 2).

Sample Cutting, First Day Epoxy Application, First Day Desiccation, Second Day

Cell Formation, Third Day Test, Third Day

Fig. 1 RCP Test Procedure

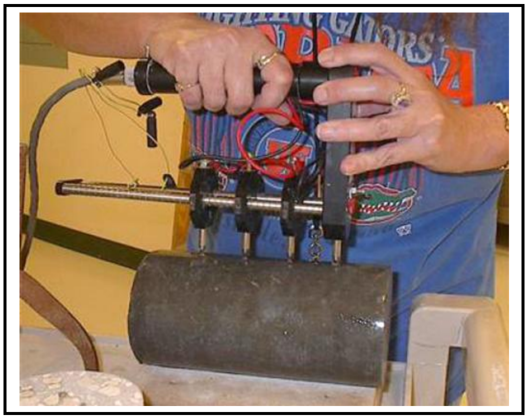


Fig. 2 SR Test Procedure

The research project correlated results from both RCP and SR tests from a wide population of more than 500 sample sets. The samples were collected from actual job sites of concrete pours in the state of Florida. The tests were compared over the entire sample population regardless of concrete class or admixture present to evaluate the strength of the relationship between the two procedures. The two tests showed a strong relationship with a level of agreement (R^2) of 0.95 for concrete specimens tested at 28 days (Fig. 3). Therefore, in 2005 SR was introduced as an alternative to RCP to characterize the chloride penetration resistance of concrete at 28 days of curing. In July 2007 the RCP test was completely eliminated from FDOT specifications and replaced with the SR Test.

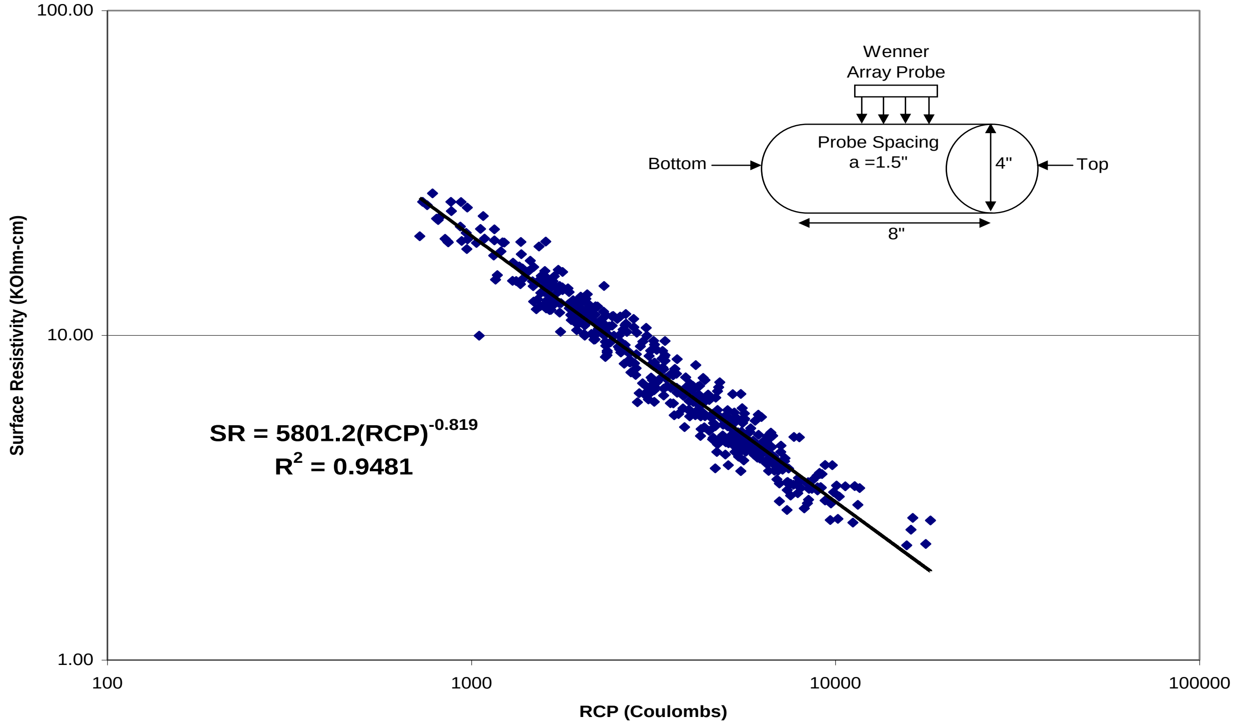


Fig. 3 RCP vs SR Correlation

A rating table to aid the interpretation of the surface resistivity results was created (Table 1) based on the previous permeability ranges provided in the standard RCP test.

Table 1 Rating Table for RCP and SR

ASTM C1202 / AASHTO T277		**Surface Resistivity Test**		
Chloride Ion Permeability	**RCP Test Charged Passed (coulombs)**	**4 X 8 Cylinder (Kohm-cm) a=1.5 (Measured)**	**6 X 12 Cylinder (KOhm-cm) a=1.5 (Measured)**	**Semi-Infinite Slab (Real)**
High	>4,000	< 12	< 9.5	< 6.7
Moderate	2,000-4,000	12 - 21	9.5 - 16.5	6.7 - 11.7
Low	1,000-2,000	21 - 37	16.5 – 29	11.7 - 20.6
Very Low	100-1,000	37 - 254	29 – 199	20.6 - 141.1
Negligible	<100	> 254	> 199	> 141.1

a = Wenner Probe spacing

While the correlation proved that the SR test could be used instead of the RCP test, the true justification for the use of the SR test had to be based on how well SR correlates to diffusion tests. The present paper reports the results of a multi-year, multi-project[5] effort carried out at the FDOT in close collaboration with the University of Florida over the last five years to characterize both the diffusion and electrical properties of fresh Florida concretes. The present document focuses on the electrical properties of concrete by use of the SR test method in water saturated concrete.

EXPERIMENTAL PROCEDURE

CONCRETE TESTED

Laboratory mixes: Table 2 presents the concrete mix design information of the laboratory specimens tested. The mixes tested included concrete without pozzolans and concrete with pozzolans such as fly ash, silica fume, metakaolin, and Super Fine Fly Ash (SFFA). Some concrete mixes with a ternary blend of cement, fly ash, and ground granulated furnace slag (GGFS) in different amounts are also included. The mix matrix also includes one mix with calcium nitrite. For these mixes, the proportions and water saturation level of the aggregates are well maintained. The data gathered come from three different projects carried out at FDOT as follows: High Reactivity Pozzolans (HRP) looked at the relative performance of fly ash, super fine fly ash, densified silica, slurry silica fume, and metakaolin. Concrete Permeability Research (CPR) looked at the correlation between the different electrical tests and diffusion tests. Ternary Blend (TB) looked at the performance of cement, fly ash, and Slag combinations.

Table 2 Laboratory Concrete Mixes

Laboratory Mixes												
Materials (Lbs/yd^3)	**CPR1**	**CPR2**	**CPR3**	**CPR4**	**CPR5**	**CPR6**	**CPR7**	**CPR8**	**CPR9**	**CPR10**	**CPR11**	**CPR12**
w/cm	0.49	0.35	0.45	0.28	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Cementitious	564	752	752	900	752	752	752	752	752	752	752	752
Cement	564	752	752	648	601.6	661.8	691.8	541.4	676.8	526.4	376	752
Fly-Ash (%)				20	20			20		20		
Lbs/yd^3				180.0	150.4			150.4		150.4		
Silica Fume (%)				8			8	8				
Lbs/yd^3				72.0			60.2	60.2				
Metakaolin (%)									10	10		
Lbs/yd^3									75.2	75.2		
GGFS (%)											50	
Lbs/yd^3											376	
Super Fine Fly Ash (%)						12						
Lbs/yd^3						90.2						
Water	276.4	263.2	338.4	252	263.2	263.2	263.2	263.2	263.2	263.2	263.2	229.5
Fine Aggregate	1,105	1,080	990	1,000	1,043	1,061	1,058	1,021	1,051	1,037	1,053	1,030
Coarse Aggregate	1,841	1,750	1,647	1,670	1,750	1,750	1,750	1,750	1,750	1,729	1,750	1,703
Calcium Nitrate (oz)												576

Table 2 Laboratory Concrete Mixes Continued

Laboratory Mixes												
Materials (Lbs/yd^3)	**HRP1**	**HRP2**	**HRP3**	**HRP4**	**TB1H5**	**TB2H5**	**TB3H5**	**TB4H5**	**TB5H5**	**TB6H5**	**TB7H5**	**TB8H5**
w/cm	0.35	0.32	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Cementitious	752	752	752	752	752	752	752	752	752	752	752	752
Cement	602	527	542	542	602	549	452	377	377	302	302	226
Fly-Ash (%)	20	20	20	20	20	20	20	10	30	20	40	10
Lbs/yd^3	150	150	150	150	150	150	150	75	225	150	300	75
Silica Fume (%)			8	8		7						
Lbs/yd^3			60	60		53						
Metakaolin (%)												
Lbs/yd^3												
GGFS (%)							20	40	20	40	20	60
Lbs/yd^3							150	300	150	300	150	450
Super Fine Fly Ash (%)		10										
Lbs/yd^3		75										
Water	263	241	263	263	263	263	263	263	263	263	263	263
Fine Aggregate	1,097	1,120	1,084	1,084	1289.9	1281.2	1284.9	1290.2	1274.6	1279.9	1264.3	1285.2
Coarse Aggregate	1,661	1,679	1,649	1,649	1468.2	1458.4	1462.5	1468.5	1450.8	1456.8	1439.1	1462.8
Calcium Nitrate (oz)												

Field mixes: Table 3 presents the concrete mix design information of the field specimens tested. These concrete mixes were made by concrete producers and FDOT was not involved in the design, batching, or mixing of these concretes. Graduate and undergraduate students from the University of Florida visited the job site or yard and sampled the concrete directly from the delivery vehicle.

Table 3 Field Concrete Mixes.

Field Mixes							
Materials (Lbs/yd^3)	**CPR13**	**CPR15**	**CPR16**	**CPR17**	**CPR18**	**CPR20**	**CPR21**
w/cm	0.45	0.29	0.33	0.34	0.30	0.28	0.29
Cementitious	569.70	565.00	807.40	840.00	842.00	1000.00	935.00
Cement	569.70	450.00	657.40	686.00	673.00	800.00	770.00
Fly-Ash (%)		20.00	19.00	18.00	20.00	20.00	18.00
Lbs/yd^3		115.00	150.00	154.00	169.00	200.00	165.00
Water	254.50	162.30	269.70	288.00	251.90	280.00	267.50
Fine Aggregate	1,434.00	1,137.00	1,048.00	935.00	973.50	868.00	727.50
Coarse Aggregate	1,655.00	1,918.00	1,724.00	1,720.00	1,914.00	1,650.00	1,918.00
Air Entrainer (oz)	0.30	2.00	1.00	5.00	4.00	2.00	5.00
Water Reducer (oz)	45.60	22.00	8.00	17.00	40.00	16.00	47.00
Super Plasticizer (oz)			70.00	55.00	110.00	52.00	110.00

BULK DIFFUSION (BD) TEST (NORDTEST NTBUILD 443)

SPECIMEN PREPARATION AND TEST SOLUTION EXPOSURE

The procedure was developed by Frederickson[6] et al and initially standardized as a test method by Nordtest, an organization founded in 1973 by the Nordic Council of Ministers. It was recently adopted by ASTM under the designation "ASTM C1556-04 Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion"**.** The main focus of the test method is to test concrete under diffusion conditions as the main driving force by minimizing the effect of absorption and permeability. Concrete specimens made were 4-inch (102-mm) diameter by 8-inch (204-mm) long, with three samples cast for each mixture. The samples were kept in a moist room with a sustained 100% humidity for 28 days, removed from the moist conditions, and sliced on a water-cooled diamond saw into two halves. The sample configuration tested is 4-inch (102-mm) diameter by 4-inch (102-mm) long cylinder. The top half was used for a 364 days (1 year) exposure period and the bottom half for 1092 days (3 years) exposure. After the exposure period, the cut specimens were immersed in a saturated $Ca(OH)_2$ solution in an environment with an average temperature of 73°F (23°C). The samples were weighed daily in a surface-dry condition until constant mass was obtained. The specimens were then sealed with Sikadur 32 Hi-Mod epoxy (on all surfaces except the saw-cut face) and left to cure for 24-hours. The sealed samples were then returned to the $Ca(OH)_2$ tanks to repeat the above saturation process by weight control. The cut face is then exposed to a 2.8 M NaCl solution (16.5% NaCl) as depicted in figure 4 and shown figure 5. The test procedure calls for an exposure period of at least 35 days for low quality concretes like those produced with high w/c and no pozzolanic admixtures. For high quality concrete mixtures, the exposure time must be extended to at least 90-days. In this program, due to the wide use of high performance concrete (HPC) in Florida, the exposure periods were 364 and 1092 day (one and three years).

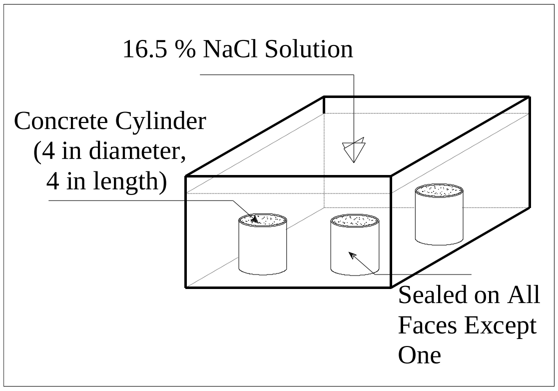


Fig. 4 Bulk Diffusion Test Setup (NordTest NTBuild 443)

Fig. 5 Bulk Diffusion Saline Solution Exposure

CHLORIDE ION CONTENT ANALYSIS

Chloride profiles are obtained immediately after the exposure period by sectioning the specimens in layers and analyzing each layer for acid soluble chlorides. Chloride ions could be present in concrete in two forms, soluble chlorides in the concrete pore water and chemically bound chlorides. The acid chloride testing technique identifies all the chlorides in each slice of concrete regardless of chemical state, so it is more conservative than water soluble chlorides test because this analysis includes those chlorides that are bound and not involved in any other reaction harmful to steel. The profile is obtained by slicing for layer thicknesses of 0.25 from the exposed face of the specimen until background levels are reached.

The FDOT has a standardized test method (FM 5-516[7]) to determine low-levels of chloride in concrete and raw materials. This wet chemical analysis method determines the sum of all chemically bound and free chlorides ions from powdered concrete samples.

APPARENT DIFFUSION COEFFICIENT CALCULATIONS

Once chloride profiles were obtained for the specimens at varying depths, the diffusion coefficients were determined by fitting the data obtained in the chloride profiles analysis to Fick's Diffusion Second Law equation. The measured chloride contents at varying depths are fitted to Fick's diffusion equation by means of a non-linear regression analysis in accordance with the method of least square fit. The Fick's Diffusion Second Law equation is presented as followed:

$$C(x,t) = C_s - (C_s - C_i)\,erf\left(\frac{x}{\sqrt{4Dt}}\right)$$

Where:

$C(x,t)$ - chloride concentration, measured at depth x and exposure time t (% mass)

C_s - projected chloride concentration at the interface between the exposure liquid and test specimen that is determined by the regression analysis (% mass)

C_i - initial chloride-ion concentration of the cementitious mixture prior to the submersion in the exposure solution (% mass)

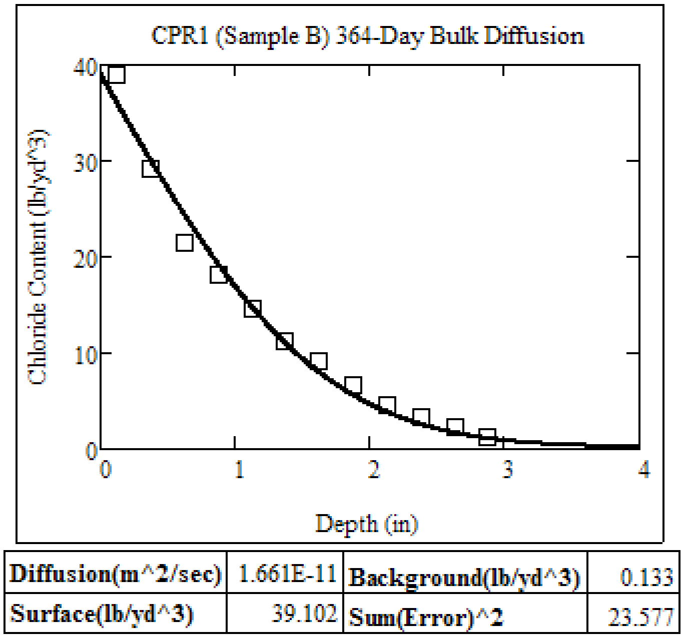
x - depth below the exposed surface to the center of a layer (m)

D - chloride diffusion coefficient (m^2/s)

t - the exposure time (sec)

erf - error function.

Fig. 6 shows an example of the regression analysis for the determination of the diffusion coefficient.



Diffusion(m^2/sec)	1.661E-11	**Background(lb/yd^3)**	0.133
Surface(lb/yd^3)	39.102	**Sum(Error)^2**	23.577

Fig 6 Diffusion Coefficient Regression Analysis

SURFACE RESISTIVITY TESTING

A procedure[8] was developed by the Florida Department of Transportation in 1996 and formalized as a test method in 2004, under the designation "FM5-578 Florida Method of Test for Concrete Resistivity as an Electrical Indicator of its Permeability". The method uses a four-point Wenner array probe resistivity meter. The set up utilizes four equally spaced surface contacts, where a 25V peak to peak, 13 Hz alternating trapezoidal voltage is passed through the concrete sample between the outer pair of contacts. The equipment measures (figure 7) the current flowing between the outer electrodes and the potential difference between the two inner electrodes, obtaining the resistance R from the ratio of voltage V to current I. This resistance is then used to calculate resistivity of the concrete section. The resistivity ρ of a prismatic section of length L and section area A is given by:

$$\rho = \frac{A \cdot R}{L}$$

The resistivity ρ for a concrete cylinder can be calculated by the following formula:

$$\rho = \left(\frac{\pi \cdot d^2}{4}\right)\frac{1}{L} \cdot \left(\frac{V}{I}\right)$$

Where d is the cylinder diameter and L its length[9].

Assuming that the concrete cylinder has homogeneous semi-infinite geometry (the dimensions of the element are large in comparison of the probe spacing), and the probe depth is far less than the probe spacing, the concrete cylinder resistivity ρ is given by:

$$\rho = \left(2 \cdot \pi \cdot a\right)\left(\frac{V}{I}\right)$$

Where a is the electrode spacing. The non-destructive nature, speed, and ease of use, make the Wenner array probe resistivity technique a promising alternative test to characterize Concrete Chloride Penetration Resistance.

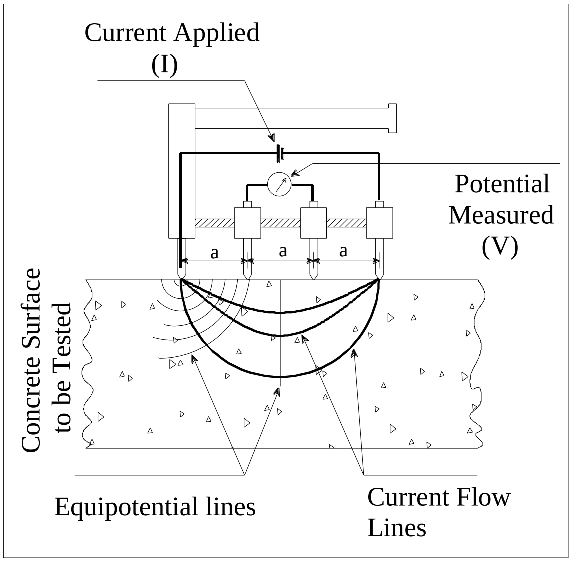


Fig. 7 Four-point Wenner Array Probe Test Setup

The resistivity of concrete can be affected if the concrete is not fully saturated. The degree of saturation was controlled by curing the specimens from the time of demolding to the time of testing in a 100% humidity condition. The conductivity of the pore solution can be affected by the different admixtures used in concrete, specifically pozzolans and corrosion inhibitors. For this research, no attempt was made to control the conductivity of the pore solution, so some contribution must be expected from the different admixtures in the concretes.

In the first project (HRP), specimens were tested at 14, 28, 56, 91, 182, 364 days, which proved to be too short to capture full resistivity development for all types of concretes, especially those with FA. For later projects (CPR and TB) additional testing ages were added to complete three full years of SR development. Commercial four tip Wenner array probe equipment was utilized for resistivity measurements. The equipment utilized wooden plugs in the end of the probes that were pre-wetted with a contact medium to improve the electrical contact transfer to the concrete. The inter-probe spacing was set to 1.5-inch (38-mm) for all measurements. On the day of testing the samples were removed from their curing environment and the readings were taken under surface wet condition. Readings were then taken with the instrument placed such that the probes were aligned with the cylinder axis. Four separate readings were taken around the circumference of the cylinder at 90-degrees increments (0^o, 90^o, 180^o and 270^o). This process was repeated once again, in order to get a total of eight readings that were then averaged.

RESULTS

Table 4 contains all the data obtained from all projects included in this paper. The data includes diffusion coefficients calculated from the BD chloride profiles (average of three calculations) at 364 and 1092 days exposure (one and three year) and SR measurements (average of 24 measurements) at all the ages specified.

Table 4 BD and SR data

Mix Information				**Pozzolan Replacement (%)**					**BD ($10^{-12}m^2/s$)**		**Surface Resistivity (KOhm-cm)**										
	Mix	**w/cm**	**cm (Lbs)**	**FA**	**SF**	**Meta**	**GGFS**	**SFFA**	**1 Year**	**3 Year**	**14**	**28**	**56**	**91**	**182**	**364**	**455**	**546**	**645**	**742**	**1092**
Laboratory Mixes	CPR1	**0.49**	**564**						18.8	26.4	6.1	6.9	7.5	7.8	9.1	9.6	11.3	10.6	11.3	11.7	12.8
	CPR2	**0.35**	**752**						4.4	4.9	8.5	9.5	10.1	10.8	11.7	12.6	14.3	13.9	14.1	15.0	21.1
	CPR3	**0.45**	**752**						9.9	10.6	5.5	5.9	6.2	6.6	7.1	7.2	9.4	8.9	9.3	10.3	14.1
	CPR4	**0.28**	**900**	**20**	**8**				1.3	0.9	25.7	44.8	63.8	78.0	81.1	89.7	112.1	106.5	116.0	126.1	177.4
	CPR5	**0.35**	**752**	**20**					5.1	2.2	6.3	8.1	12.6	18.5	28.6	35.0	47.3	45.4	48.0	47.1	76.0
	CPR6	**0.35**	**752**					**12**	4.8	3.7	5.9	7.2	9.6	12.7	18.3	23.7	26.9	28.5	31.3	33.9	34.0
	CPR7	**0.35**	**752**		**8**				2.1	2.0	16.6	28.7	38.8	40.7	41.3	42.1	46.8	43.6			48.0
	CPR8	**0.35**	**752**	**20**	**8**				2.9	2.6	13.8	24.3	33.1	38.9	46.2	56.5	59.6	65.2	70.7	70.6	69.8
	CPR9	**0.35**	**752**			**10**			1.1	1.4	38.7	33.5	39.3	38.9	43.5	60.0	51.5	55.6	55.7	63.4	61.5
	CPR10	**0.35**	**752**	**20**		**10**			2.4	2.1	34.6	31.7	37.6	43.5	56.6	85.3	82.7	90.3	101.8	105.2	113.8
	CPR11	**0.35**	**752**				**50**		2.7	2.3	13.3	17.4	20.8	22.5	25.2	31.4	34.1	34.6	36.7	38.3	39.8
	CPR12	**0.35**	**752**						7.2	11.5	8.1	8.9	9.7	9.9	10.9	12.3	12.9	12.9			13.5
	HRP1	**0.35**	**752**	**20**					3.0		5.1	7.3	10.8	19.7	30.6	42.8					
	HRP2	**0.32**	**752**	**20**				**10**	1.3		5.5	13.9	25.4	47.9	69.1	106.7					
	HRP3	**0.35**	**752**	**20**	**8**				1.8		10.7	25.6	38.2	29.2	51.5	60.7					
	HRP4	**0.35**	**752**	**20**	**8**				1.7		12.9	29.6	43.8	30.2	48.9	66.6					
	TB1H5	**0.35**	**752**	**20**					1.1		7.4	9.3	14.6	22.6	40.1	43.7					
	TB2H5	**0.35**	**752**	**20**	**7**				1.0		16.2	29.8	56.7	82.9	42.4	90.7					
	TB3H5	**0.35**	**752**	**20**			**20**		0.9		9.9	12.3	23.8	33.2	29.7	58.1					
	TB4H5	**0.35**	**752**	**10**			**40**		1.1		15.6	19.6	34.5	42.9	30.5	54.4					
	TB5H5	**0.35**	**752**	**30**			**20**		0.8		11.0	20.4	35.7	51.2	43.3	91.9					
	TB6H5	**0.35**	**752**	**20**			**40**		1.0		14.4	25.5	40.9	52.4	37.8	79.4					
	TB7H5	**0.35**	**752**	**40**			**20**		1.5		9.1	17.6	28.9	45.0		80.3					
	TB8H5	**0.35**	**752**	**10**			**60**		0.7		22.0	36.0	49.6	62.9		66.3					
Field Mixes	CPR13	**0.45**	**569.7**						10.1	25.4	6.2	6.5	7.6	8.2	8.7	9.4	11.0	10.9	9.8	10.7	11.8
	CPR15	**0.29**	**565**	**20**					5.1	10.5		7.9	8.8	10.0	16.7	23.3	24.6	28.5	27.4	27.8	27.2
	CPR16	**0.33**	**807**	**18**					5.8	3.2	7.3	7.7	10.6	15.3	21.9	29.6	37.2	37.8	34.4		44.8
	CPR17	**0.34**	**840**	**18**					4.4	2.5		11.6	15.5	20.7	28.6	33.4	33.2	39.6	38.0	38.6	39.9
	CPR18	**0.3**	**842**	**20**					2.3	2.0		14.0	16.4	36.1	61.6	94.2	92.7	119.2	113.7	119.0	129.6
	CPR20	**0.28**	**1000**	**20**					2.5	2.2		13.1	14.9	22.8	32.7	42.1	40.2	49.9	46.6	50.6	50.9
	CPR21	**0.29**	**935**	**18**					2.4	1.4		12.9	16.3	20.0	42.1	66.4	70.4	86.6	80.9	85.5	82.5
Correlations of BD vs. SR at different ages					BD 1 Year Correlation						0.318	0.550	0.698	0.788	0.641	0.735	0.708	0.697	0.700	0.736	0.676
					BD 3 Year Correlation						0.499	0.538	0.613	0.738	0.803	0.779	0.794	0.770	0.764	0.779	0.808

CORRELATION OF SURFACE RESISTIVITY vs. BULK DIFFUSION

Surface resistivity results from all mixes at the different testing ages (14, 28, 56, 91, 182, 364, 455, 546, 645, 742, and 1092 days of age) were individually compared to the 364-Day and 1092-Bulk Diffusion results in linear plots. A mathematical curve-fitting was then derived for each of the test correlations. The power regression was selected as the most adequate trend relationship between the two set of test results. Figure 8 shows a detailed graph of the test correlation with the respective derived least-square line-of-best fit for the 91 day SR versus the 364 and 1092 BD.

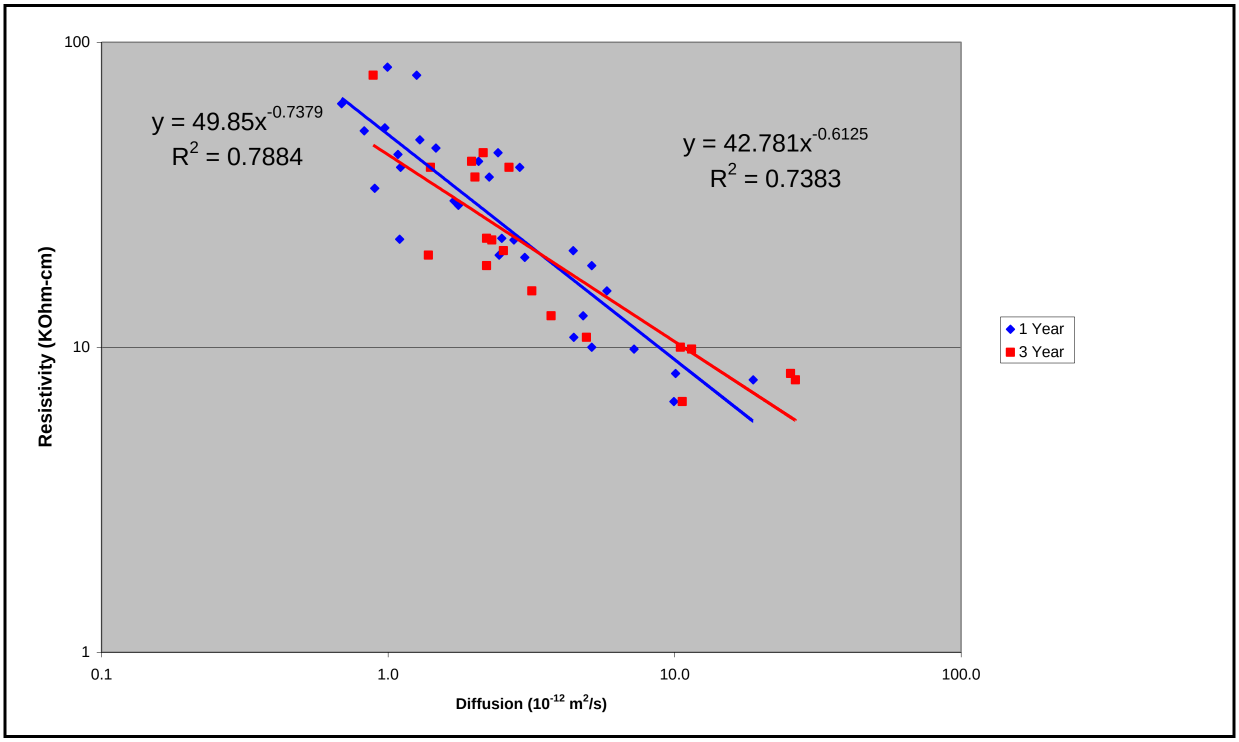


Fig. 8. 91 day SR correlation to 1 and 3 year BD

The most significant test result is that SR does correlate well to BD and therefore it can be used as a quality control procedure as long as it is calibrated to the long term diffusion tests. The correlation gets better as the concretes with slow reaction kinetics reach maturity (Fig. 9). Once the concretes reach 91 days of curing age, the correlation between the two test methods maximizes, allowing the SR test to be used as an indicator of chloride penetration resistance.

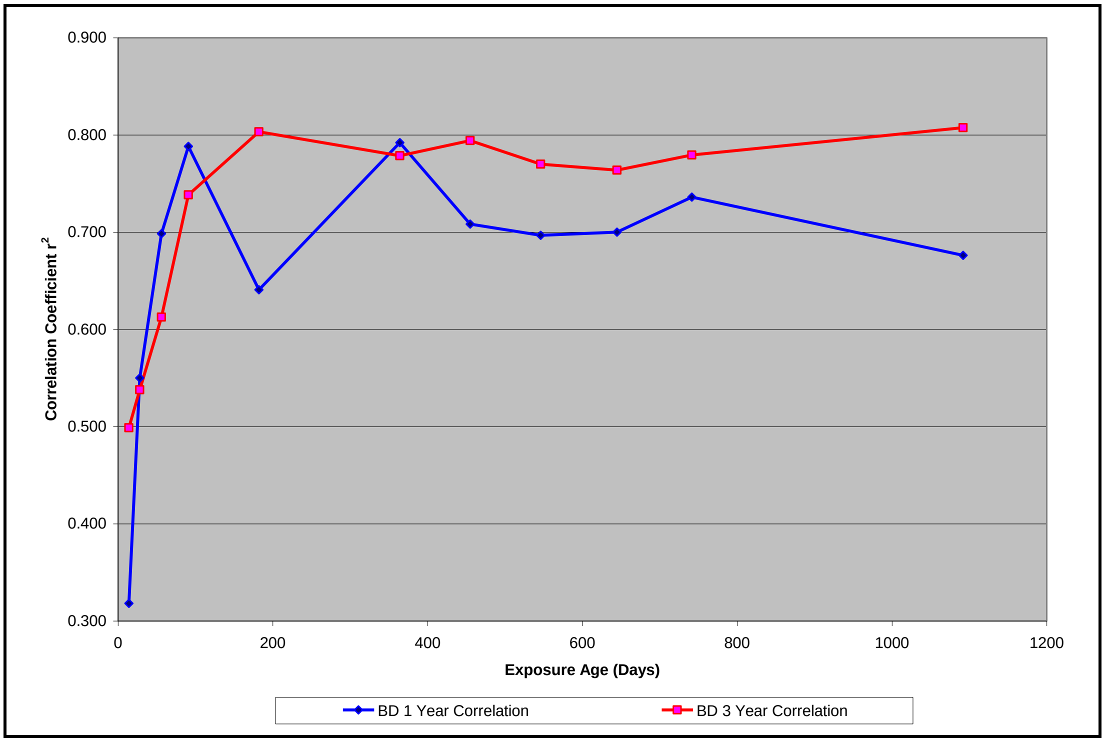


Fig. 9 SR to BD Correlation Coefficient

The correlation factor of SR to diffusion is slightly better than those reported for RCP[5] for all ages and worse that those reported for the Rapid Migration Tests (RMT)[10] at early ages and only slightly worse at later ages. The differences in correlation factor between the three tests are small enough that either one can be used with good confidence once the testing age of 91 days is reached. When one takes into account the steps involved to prepare the specimen for testing and the time involved to carry out the tests, it is clear that SR has the best combination of speed, ease of use, repeatability, and good correlation to diffusion tests.

SURFACE RESISTIVITY DEVELOPMENT FOR SIMILAR MIXES WITH DIFFERENT MINERAL ADMIXTURES

Mineral admixtures are ingredients other than water, aggregates, cement, and plastic property modifying chemicals that are added to the concrete batch during mixing to improve chloride penetration resistance. The majority of the laboratory concrete tested was designed using as a guideline the lowest quality concrete allowed by FDOT specifications in a highly aggressive marine environment. For these environments the minimum amount of cementitious allowed is 752 Lbs/yd^3 and the maximum w/cm of 0.35. The mineral admixture replacement proportions used were as allowed in the specifications as well. The type and amount of aggregate was maintained as constant as possible while attempting the keep the fine to coarse aggregate ratio the same for the mix designs. Fig. 10 displays the development of SR at early ages and Fig. 11 shows the full SR spectrum for all the ages tested. The concretes are maintained in a 100% humidity curing environment through out the whole process. A shaded marker is used for those mixes where more than one mineral admixture was used. Not every mix is represented in the figure, as this would make it nearly impossible to follow the important differences of the different mineral admixtures. A 0.45 w/cm mix is included to observe the influence of w/cm. A mix with Calcium Nitrite is also included to demonstrate the effect of an ionic chemical admixture that may lower the resistivity of the water contained in the pore system.

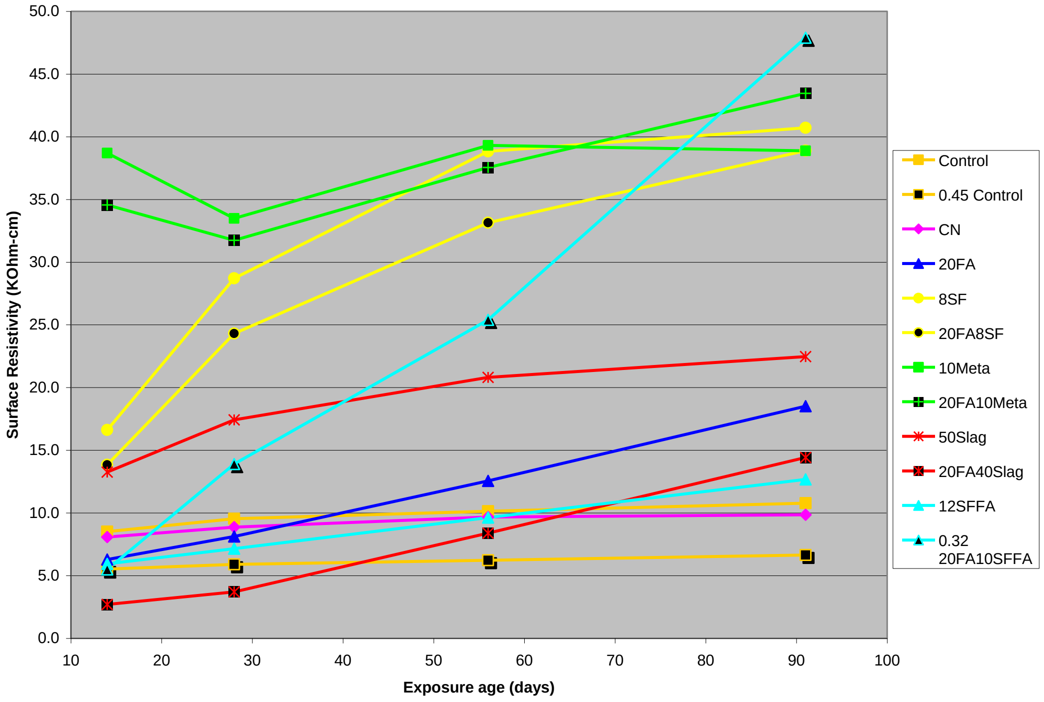


Fig. 10 Early age SR development for select mixes

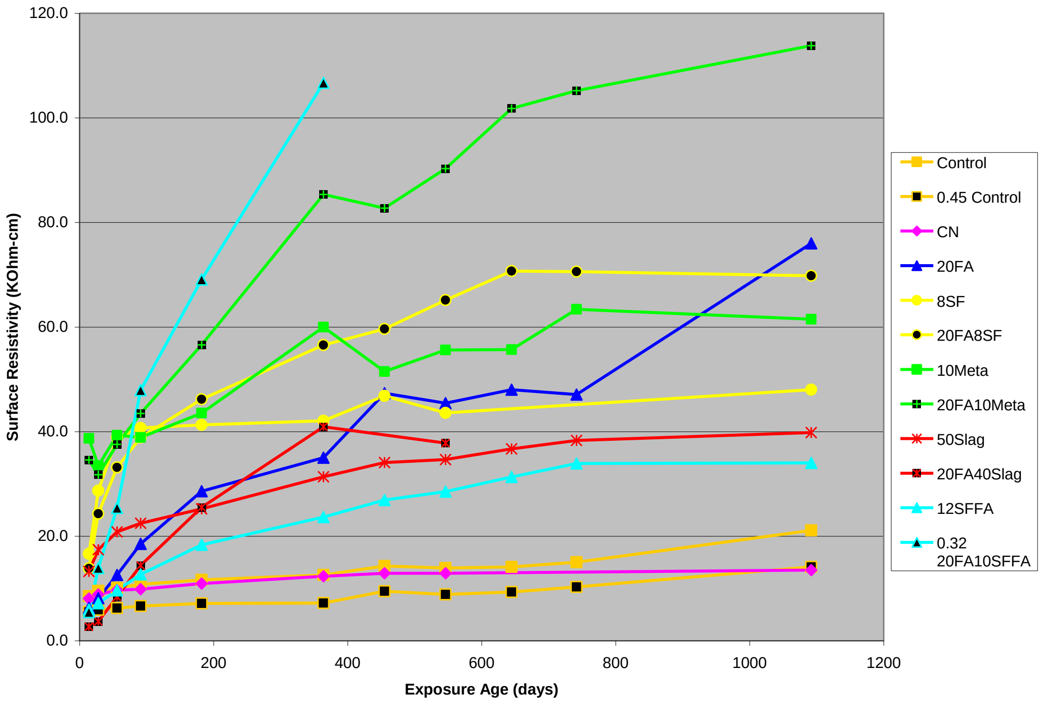


Fig. 11 SR development for select mixes

The following information is evident from Figs. 10 and 11.

1. Cement by itself sees limited (less than twice) improvement over time in SR with respect to the first reading.
2. Fly ash, slag, and super fine fly ash by themselves actually lowered the SR at early ages compared to the control specimens, indicating that they do not react significantly initially and because of the reduced amount of cement the SR value is lowered.
3. Metakaolin provides the highest SR value at early ages
4. Silica Fume and metakaolin react almost completely in the first 91 days.
5. All mineral admixtures display a large improvement in SR (more than twice)
6. Each mineral admixture has its own rate of SR development; indicative of the different reactions rates of the mineral admixtures added.
7. The combination of super fine fly ash and fly ash with a lower w/c provides the most improvement in SR for the 1 year exposure period.
8. The combination of fly ash and metakaolin provides the best improvement in SR over 3 years of exposure.

All this information indicates that it is possible to produce a mix with high SR if the proper combination of total cementitious amount, w/cm, and mineral admixture is found and optimized. The question still remains as to whether the mix which achieves the maximum SR is indeed the mix with the lowest diffusion characteristics and vice versa. If SR is a good indicator of chloride penetration resistance, then the mix which achieves the highest value at the earliest possible time would be the mix with the best chloride penetration resistance.

DIFFUSION PERFORMANCE

The best coefficient obtained of all the concretes studied was about $1x10^{-12}$ m^2/s. The diffusion coefficient is one order of magnitude higher that those reported in previous work[5,10] for field specimen cores of $1x10^{-13}$ m^2/s obtained from actual structures with similar mineral admixtures. This could be partly explained by the immaturity of the concrete at the initial exposure age of 28 days and the limited exposure length period of the laboratory diffusion tests. Some concretes, such as the ones with fly ash, or slag, will not be fully reacted for a long portion of the exposure period. As SR demonstrates, not all mineral admixtures develop at the same rate and not all mixes reach the same level of resistivity, so if one assumes that SR is an indicator of chloride penetration resistance then those concretes with slow reacting mineral admixtures should have higher diffusion coefficients than those with silica fume or metakaolin which achieve high resistivity values very early in their curing age. Table 4 reveals that for the concretes studied, the only way to achieve diffusion coefficients of less than $3x10^{-12}$ m^2/s is by the addition of mineral admixtures in the concrete for the 1 year exposure period. For the 3 year exposure period, the only way to achieve $4x10^{-12}$ m^2/s is by the use of mineral admixtures. In fact, only on the concretes with mineral admixtures was a decrease in diffusion coefficient observed from the 1 to 3 year exposure periods, while those without them displayed an increase in diffusion coefficient.

CONCLUSION

SR can be used as an electrical indicator of concrete chloride penetration resistance. Specifically it can be used at 28 days on all those concretes whose components have completed a large portion of their total reaction like those concretes with silica fume or metakaolin. For concretes with fly ash, super fine fly ash, or slag which are slow to react, a later age like 91 days, may be more appropriate. The test should be used as a quality control predictor of the chloride penetration resistance of the concrete, but not as a predictor of diffusion behavior for all kinds of concretes or as replacement of the long term diffusion tests. The long term diffusion tests should still be used when new concrete formulations are used in order to establish if the relationship between electrical properties and diffusion properties still hold.

The diffusion behavior of laboratory specimens is one order of magnitude higher that those reported from field concrete. This is partially due to the fact that the diffusion samples are exposed to chloride ions at a curing age in which the concrete is still immature.

The resistivity development rate is different for the different mineral admixtures, but it is possible to obtain a high resistivity if the right combination of total cementitious, w/cm, and mineral admixtures are used.

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