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Simplified Concrete Resistivity and Rapid Chloride Permeability Test Method

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A simplified method of measuring concrete resistivity, as an index of permeability, has been developed that is similar to ASTM C1202 or the rapid chloride permeability test (RCPT). It is significantly faster and easier to perform, however. In this test, cylinders 100 x 200 mm (4 x 8 in.) were cured in 100% relative humidity and tested using the same solutions, test cells, and rubber gaskets as specified in ASTM C1202. To eliminate the problem of the temperature rise of the sample during the test, only one current reading was taken (after 5 minutes) that could be used to calculate the concrete resistivity. Testing was conducted on various different concrete mixtures after 91 days of moist curing using both the new quicker method and the standard ASTM C1202 method. An empirical correlation between the new method and the standard method demonstrates the validity and promise of the new method.

Keywords: concrete permeability; rapid chloride permeability test; resistivity.

INTRODUCTION

First developed by Whiting,[1] ASTM C1202, or the rapid chloride permeability test (RCPT),[2] has become a common test to assess concrete's ability to resist chloride intrusion. The test method is commonly used because it is relatively quick (approximately 24 hours for sample preparation plus an additional 6 hours for testing) and inexpensive as opposed to the alternative AASHTO T 259 salt ponding test, which takes at least 119 days to perform after concrete curing.[3]

ASTM C1202 measures the electrical conductivity of a 50 mm (2 in.) thick concrete disk over a 6-hour time period. The current readings taken are then integrated over the 6-hour period to obtain the final charge passed.[2] Because it is the electrical conductivity (or resistance) that is measured, the test is really a long-duration resistivity test. It is assumed that the resistivity is directly related to the tortuosity of the pore network or concrete permeability, although the relation is not perfect.[4]

One problem with ASTM C1202 is that the current tends to increase during the test, especially with low quality/high-permeability concrete, because the specimens heat up, thus increasing the conductivity. Furthermore, chloride ions may migrate in while hydroxyl ions migrate out, changing the concrete conductivity.[5,6] Another problem with ASTM C1202 is the amount of sample preparation needed. Sample cutting, vacuum saturation, and testing take at least 24 hours to complete. Additionally, sample cutting can introduce a significant amount of variation in the test method. Two samples both cut according to ASTM C1202 could have a difference in length between the two of 6 mm (1/4 in.) or over 12%. The samples may also not be reused because of concerns over leaching in a moist environment and the exposure to chlorides during the test, which may change the pore solution conductivity.

It is well known that ASTM C1202 may give a false estimate of the concrete chloride diffusion when some supplementary cementing materials are used, especially silica fume,[6,7] when some chemical admixtures such as calcium nitrite are used or when steel fibers or reinforcing steel bars are present.[2] Some supplementary cementing materials (SCMs) and chemical admixtures change the pore solution hydroxyl or other ionic species concentration. This can change the electrical conductivity of the concrete without necessarily changing the tortuosity of the pore structure.[5] Because of their high electrical conductivity, steel fibers or reinforcing bars cause very low resistance values in ASTM C1202, even though they do not fundamentally change the concrete pore structure (ASTM C1202 2005).

In spite of its flaws, ASTM C1202 or any other electrical resistivity-based test may still be useful for quality control to detect radical changes in the water-cementitious material ratio (*w/cm*) or material properties. It is also useful to know the concrete electrical resistivity for modeling the galvanic cell that is formed after corrosion has initiated.[2,8]

Previous research has suggested that the current RCPT may be greatly simplified. Scali et al.[9] first suggested that the permeability test could be simplified into just a resistivity test; conversion factors are used to achieve the same results as ASTM C1202. In other studies, good correlations were shown between the initial current readings, or conductance, and the total charge passed for a limited number of concrete samples. These tests were conducted on a limited variety of blended cements and chemical admixtures.[6,7,10,11]

Several other methods have been developed for measuring the chloride permeability of concrete. Electrical methods include the electrical migration technique, the rapid migration test, concrete resistivity,[8] and alternating current (AC) impedance techniques.[5,10] The electrical migration technique is similar to ASTM C1202, but the chloride ion concentration is measured in the anode solution instead of simply measuring the total charge passed through the concrete during a 6-hour period of time. In the rapid migration tests, an electrical charge is applied to the sample, after which the sample is split and the depth of chloride penetration is determined using chemical indicators. Concrete resistivity tests are simple measures of the concrete's electrical resistance per unit cross section and length.[8] AC impedance measurements are similar to resistivity measurements, except that an alternating current is used instead of a direct current (DC). Pressure and temperature have also been used

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as driving forces to speed up chloride diffusion in concrete for direct measurement. ASTM C1556, the concrete bulk diffusion test, uses high temperatures to speed up the diffusion of chloride ions into concrete.[12]

A new, simplified method of performing ASTM C1202 has been developed and is reported herein. The method greatly simplifies the sample preparation needed on lab-cured samples to measure the rapid chloride permeability of concrete. The new test uses the same setup as ASTM C1202, except that specimen was cured at 100% relative humidity instead of vacuum saturation. The specimen was 200 mm (8 in.) in length and uncut, and the specimen was only tested for 5 minutes. The total test may now take less than a half hour from sample setup to finish. The new test method also can be run with only minor modifications to existing ASTM C1202 testing equipment, and the same test cylinder can be tested at a given age, returned to moist-curing conditions, and retested at subsequent ages. Additionally, because the test is run for such a short duration, the sample temperature increase should be negligible. Because this new test method is so similar to ASTM C1202 and can use the same equipment, practitioners can easily implement this new test method.

RESEARCH SIGNIFICANCE

Corrosion of reinforcing steel is the largest durability problem worldwide in concrete structures. Engineers have been specifying high-performance concrete (high strength/low permeability) in recent years in an effort to reduce concrete chloride diffusion and increase the service life of structures. In this paper, a simplified procedure for measuring electrical resistivity of concrete containing different types of cements and supplementary cementing materials is described. The test method may serve as a quick and inexpensive quality control test for concrete construction.

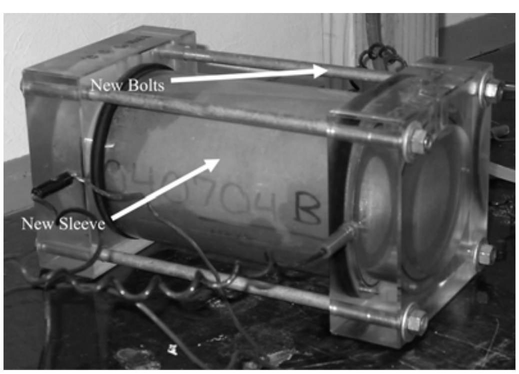

Fig. 1—Simplified RCPT test setup.

EXPERIMENTAL METHODS

ASTM C1202,[2] the RCPT, was used to evaluate 117 concrete mixtures. After 91 days of moist curing, two 50 mm (2 in.) specimens were cut from the same 100 x 200 mm (4 x 8 in.) cylinder for each mixture. Both specimens for each batch were tested according to ASTM C1202.[2] Specimens were tested using rubber gaskets instead of silicone rubber caulking to prevent leakage of the solution, as allowed by ASTM C1202.[2] The total charge passed during the 6-hour test, as well as the initial voltage drop across the sample, was recorded.

Fifty-five of the concrete mixtures tested according to ASTM C1202[2] were also tested at 91 days using a simplified version of the RCPT method, hereafter called the simplified RCPT. The test was conducted using the same electronic equipment, ionic solutions, and voltage cells as used in ASTM C1202.[2] The differences were as follows. The simplified RCPT method was conducted on a full 100 x 200 mm (4 x 8 in.) cylinder using a 188 mm (7.4 in.) long acrylic sleeve, as shown in Fig. 1, instead of the shorter 50 mm (2 in.) specimen and 36 mm (1.4 in.) sleeve prescribed by the ASTM C1202[2] test. In the simplified RCPT method, the sample was taken directly out of the curing room (100% relative humidity) and tested; no vacuum desiccation was performed. In the simplified RCPT method, only the voltage drop across the sample after 5 minutes was recorded; the total charge passed through the sample was not recorded.

To illustrate the effect of temperature on the resistivity of concrete, cylinders from three different concrete mixtures were placed overnight in water at 38 and 60 °C (100 and 140 °F) and in the 23 °C (73 °F), 100% relative humidity chamber. The three concrete mixtures were over a year old to reduce the effects of the temporary high temperature on hydration and leaching. The samples were tested for resistivity using the simplified RCPT method.

CONCRETE MATERIALS

A wide variety of materials were tested using ASTM C1202.[2] Several types and brands of ASTM C494[13] Type A water reducer, mid-range water reducer, and ASTM C494[13] high-range water reducer were used. One type of calcium nitrate-based accelerator was used in four mixtures, and a calcium nitrite corrosion-inhibiting admixture was used in one mixture. The value of *w/cm* ranged from 0.32 to 0.53 for the ASTM C1202[2] tests and 0.32 to 0.50 for the simplified tests, with the majority being between 0.40 to 0.44. Three types of ASTM C618[14] Class C fly ash were used, whereas five types of ASTM C618[14] Class F fly ash were used. One type each of silica fume, ultra-fine fly ash, and Grade 120 ground-granulated blast-furnace slag (GGBFS)[15] were used in the study. Table 1 summarizes the number of material sources and the number of mixtures that contained each type of material for the tests performed according to ASTM C1202[2] and the simplified RCPT method. As seen in Table 1, not all mixtures were tested using the simplified RCPT method. Table 2 summarizes the range of material quantities used in the study. When comparisons between tests were made, concrete cylinders from the same concrete batches were tested using each test.

RESULTS

The initial readings taken during the testing for the ASTM C1202[2] test and the simplified RCPT method were converted to resistivity values using Eq. (1)

$$\rho_c = \left(\frac{(E_s - 2) \cdot R}{E_m}\right) \cdot \left(\frac{A}{L}\right) \tag{1}$$

where ρ_c is the concrete resistivity (Ω-m), E_s is the supplied DC voltage (60 V), R is the resistance provided by the shunt resistor (0.01 Ω), E_m is the voltage drop measured, A is the cross-sectional area of the cylinder (m^2), and L is the length of the specimen (m). Following the method suggested by Arup et al.,[6] two volts are subtracted from the supplied voltage to account for "the voltage loss due to polarization of the electrodes (or the voltage loss in electrolyzing water and forming hydrogen and oxygen)." Figure 2 shows a comparison of the average calculated resistivity values for the two samples tested for each mixture using ASTM C1202[2] versus the simplified RCPT method. Figure 3 shows the resistivity values measured for the first ASTM C1202[2] sample versus the values measured for the second ASTM C1202[2] sample from the same concrete batch to illustrate the inherent scatter in the ASTM C1202[2] test method itself. The r^2 value of 0.97 shown in Figure 3 is an indicator of how well the two tests relate. A perfect match between the two tests would give an r^2 value of 1. As shown in Fig. 2 and 3, the scatter from the resistivity tests obtained from the simplified test method is higher at the higher resistivity values. This increased scatter may be because of the 200 mm (8 in.) sample length in the simplified RCPT method, which results in more resistance and hence a lower voltage drop. The voltmeter used in this study is not sensitive enough to distinguish between very dense concrete with very low voltage drops. This leads to an increase in scatter in the data with concrete with a high electrical resistivity. A higher precision voltmeter or measurement of the sample current instead of voltage drop would reduce this scatter in the higher resistivity values.

Another way to compare the two tests is using a method suggested by Arup et al.,[6] who calculated equivalent coulomb values from the initial readings assuming a constant voltage drop during a 6-hour period. These calculated values for the simplified RCPT method are compared with the measured values of total charge passed from the ASTM C1202[2] test. The coulomb values from the simplified test are multiplied by 4 to compensate for the length of the specimen. The data from the simplified test were extrapolated to an equivalent 6-hour charge passed to facilitate a direct comparison of the two test methods. Figure 4 shows a comparison of the coulomb readings for the simplified RCPT method assuming a constant voltage drop during 6 hours versus the average of the two coulomb values for a full 6-hour ASTM C1202[2] test. Figure 4 clearly shows that the differences between the two test methods examined in this study are very predictable.

Table 1—Number of sources and mixtures for different mixtures used in testing

Material	ASTM C1202 No. of sources	ASTM C1202 No. of mixtures	Simplified method No. of sources	Simplified method No. of mixtures
Type I cement	3	47	2	14
Type I/II cement	6	58	5	28
Type V cement	1	12	1	12
Class F fly ash	5	34	5	13
Class C fly ash	3	28	3	12
GGBFS	1	12	1	6
Ultra-fine fly ash	1	7	1	4
Silica fume	1	7	1	2

Table 2—Material amount ranges used

	ASTM C1202 Minimum	ASTM C1202 Maximum	Simplified method Minimum	Simplified method Maximum
Calcium nitrite-based corrosion inhibitor L/100 kg of total cementing materials (gal./100 lb of total cementing materials)	0	8.3 (1)	0	8.3 (1)
Calcium nitrate-based accelerator L/100 kg of total cementing materials (gal./100 lb of total cementing materials)	0	2.2 (0.26)	0	2.2 (0.26)
w/cm	0.32	0.53	0.32	0.5
Class F fly ash, % replacement	0	55	0	31
Class C fly ash, % replacement	0	40	0	40
GGBFS, % replacement	0	70	0	70
Ultra fine fly ash, % replacement	0	9	0	8
Silica fume, % replacement	0	10	0	10

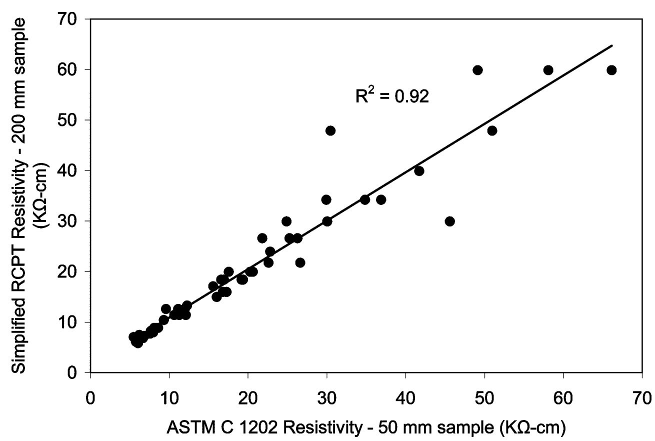

Fig. 2—Resistivity values for ASTM C1202 method versus simplified RCPT method. (Note: 1 KΩ-cm = 0.394 KΩ-in.)

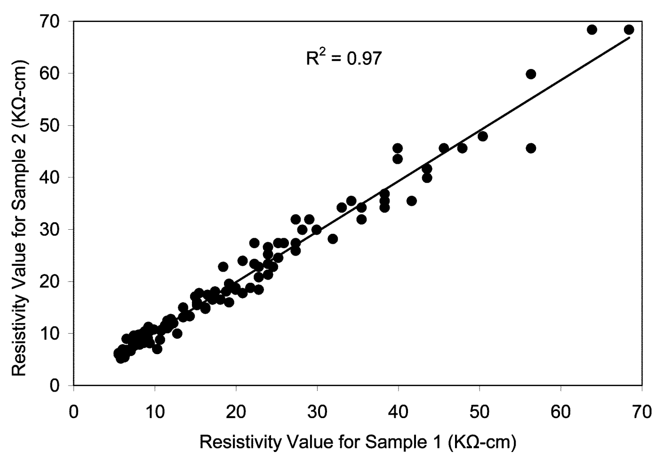

Fig. 3—Comparison of resistivity values from two samples tested from same concrete batches using ASTM C1202. (Note: 1 KΩ-cm = 0.394 KΩ-in.)

The data presented in Fig. 4 from the ASTM C1202[2] and the simplified RCPT methods were combined with similar data from previous studies where DC resistivity values were collected at the same time as ASTM C1202[2] values. This joint data set was used to develop an empirical model to relate the increase in charge passed during a 6-hour time period to that extrapolated from initial values. This relationship is also shown in Fig. 5. The values for concrete at early ages from Feldman et al.[7] were not included in the data set because heating during the 6-hour test can increase the hydration reaction, changing the results expected. A quadratic trend worked well to describe the increase in charge passed during the 6-hour time, as shown in Eq. (2)

$$Q_{6h} = 0.0000205Q_i^2 + 0.8758Q_i \tag{2}$$

where Q_{6h} is the charge passed during a full ASTM C1202[2] test (coulombs), and Q_i is the charge for a 6-hour period extrapolated from one initial current reading normalized to a 50 mm (2 in.) length (coulombs). Equation 2 is nonlinear because of heating that occurs in the samples and, to a lesser extent, chloride ion movement, especially in more porous concrete. Equation (2) may be used to develop a concrete rating system similar to that used in ASTM C 1202[2] based on the simplified RCPT method extrapolated to 6 hours of charge passed. The new concrete classification guidelines recommended for use with the new simplified RCPT method are shown in Table 3.

EFFECTS OF TEMPERATURE

The three concrete mixtures tested at different temperatures using the simplified method decreased in resistivity with increasing temperature, as expected. As shown in Fig. 6, the temperature dependence of concrete resistivity follows Eq. (3)[5]

$$\rho_c(T) = \frac{1}{A\exp\dfrac{-\Delta E}{(k_b T)}} \tag{3}$$

where A and ΔE are empirical constants determined for each mixture, k_b is Boltzmann's constant, and T is the absolute temperature (K). The concrete resistivity increased by 92, 71, and 65% for the three concrete mixtures when the temperature was increased from 23 to 60 °C (73 to 140 °F). As the data in Fig. 6 shows, the simplified RCPT method can be used to measure the temperature dependence of the concrete mixture resistivity. These data can be useful for modeling the galvanic current present once reinforcing steel corrosion, which is dependent on the concrete resistivity, has initiated. The modeling of the galvanic current may prove useful in service-life models to determine the rate of corrosion and the possible extent of damage from corrosion.

ADVANTAGES AND DISADVANTAGES OF SIMPLIFIED RCPT

The simplified RCPT method greatly simplifies the test procedure found in ASTM C1202[2] for determining the

Table 3—Recommended guidelines for equivalent concrete classification based on initial current reading

Concrete permeability	Charge passed during full 6-hour test, coulombs	Extrapolated charge from initial reading normalized to 50 mm (2 in.) length for simplified RCPT, coulombs
Very low	<1000	<900
Low	1000 to 2000	900 to 1600
Moderate	2000 to 4000	1600 to 3000
High	>4000	>3000

Note: 1 mm = 0.0394 in.

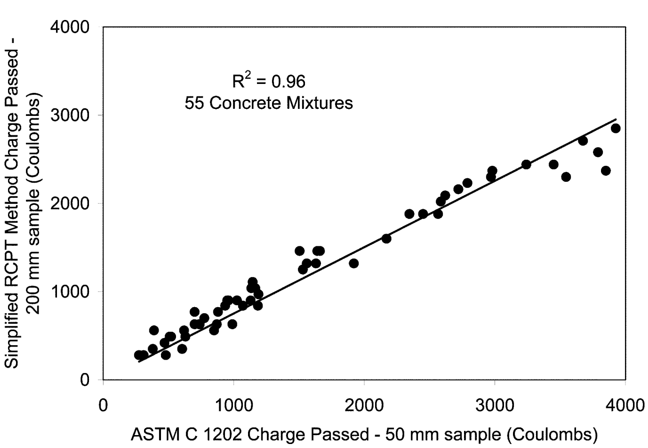

Fig. 4—Comparison of ASTM C1202 test to simplified RCPT method assuming constant current. (Note: 1 mm = 0.0394 in.)

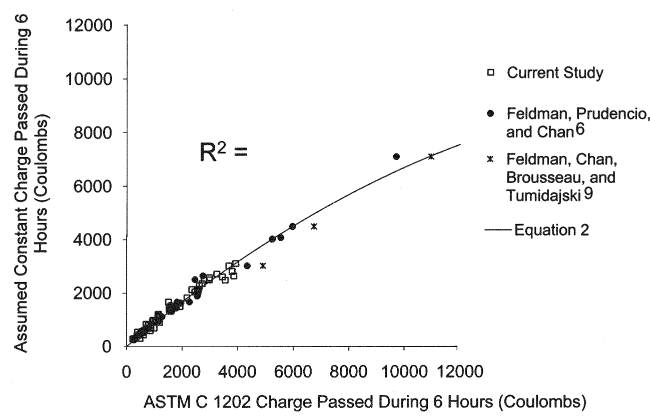

Fig. 5—Comparison of coulomb values extrapolated from initial resistivity reading in simplified RCPT method to total charge passed in 6-hour ASTM C1202 test.

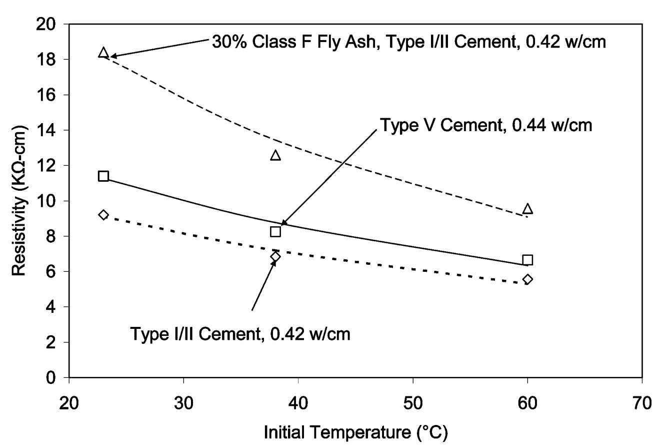

Fig. 6—Concrete resistivity versus concrete temperature at testing using simplified RCPT method. (Note: 1 °C = 1 °F; 1 KΩ-cm = 0.394 KΩ-in.)

electrical resistivity of concrete. The simplified RCPT method gives results that are comparable to those obtained from ASTM C1202[2] as shown in Fig. 2, 4, and 5. The procedure eliminates saw cutting and the inherent problems and variability associated with it. The simplified RCPT method can be run very quickly; consequently, the specimen temperature does not increase during the test and change the charge passed. The test method may also be used as a simple indicator of the concrete permeability based on revised guidelines for interpreting the data shown in Table 3. The simplified RCPT method for concrete resistivity may serve as an important method for characterizing the temperature dependence of concrete resistivity on temperature for modeling the corrosion rate in service-life models. Additionally, the specimens may be reused at a later age to track the change of the concrete resistivity with time.

The simplified RCPT method does not solve all of the problems associated with the RCPT method. Because the new test is still an electrical test, changes in pore solution chemistry will still register a change in the measured values that may not be indicative of a change in porosity and pore structure tortuosity. The test method may also produce a large amount of scatter when the voltage is measured instead of current at higher concrete resistivity values. Using a more sensitive voltmeter, however, may eliminate this problem.

CONCLUSION

A simplified method for quickly measuring the concrete resistivity and corresponding rapid chloride permeability value has been developed. The test is based on the procedures outlined in ASTM C1202,[2] simplified to avoid cutting samples, desiccation, test duration, and sample heating. Specimens containing various cement types, supplementary cementing materials, *w/cm*, and chemical admixtures were tested using the new simplified test and ASTM C1202[2] for comparison. The correlation between the simplified RCPT and the ASTM C1202[2] worked well for all materials tested. The difference in values obtained from the two different tests was due mainly to concrete heating that occurred during the ASTM C1202[2] test and was found to be very predictable. A correlation between the two tests and implementation guidelines were also developed. The simplified procedure is advantageous in that existing RCPT equipment may be used—the only modification being a longer acrylic sleeve around the concrete and longer bolts to provide compression to the rubber gaskets. The test method may also be used to determine the temperature dependence of concrete resistivity for a particular concrete mixture. The test method, like other electrical methods, does not directly measure the chloride diffusion of a concrete sample. The method has only been performed on laboratory-cured samples, and its suitability for cored field samples has not yet been determined.

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NOTATION

C	=	ASTM C618 Class C fly ash
F	=	ASTM C618 Class F fly ash
GGBFS	=	ground-granulated blast-furnace slag
HRWR	=	ASTM C494 Type F high-range water-reducing admixture
LRWR	=	ASTM C494 Type A water-reducing admixture
MRWR	=	mid-range water reducer

REFERENCES

1. Whiting, D., "Rapid Determination of the Chloride Permeability of Concrete," *Final Report* No. FHWA/RD-81/119, Federal Highway Administration, NTIS No. PB 82140724, 1981.
2. ASTM C1202, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration," ASTM International, West Conshohocken, PA, 2005, 6 pp.
3. AASHTO T 259-02, "Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration," AASHTO Standard Specification, American Association of State Highway and Transportation Officials, Washington, DC, 2002.
4. Mindess, S.; Young, J. F.; and Darwin, D., *Concrete*, second edition, Pearson, Education, Inc., Upper Saddle River, NJ, 2003, 644 pp.
5. Beaudoin, J. J., and Liu, Z., "The Permeability of Cement Systems to Chloride Ingress and Related Test Methods," *Cement, Concrete and Aggregates*, V. 22, No. 1, June, 2000, pp. 16-23.
6. Arup, H.; Sørensen, B.; Frederiksen, J.; and Thaulow, N., "The Rapid Chloride Permeation Test—An Assessment," *Paper* 334, Corrosion93, The NACE Annual Conference and Corrosion Show, 1993, 11 pp.
7. Feldman, R.; Prudencio, L. R.; and Chan, G., "Rapid Chloride Permeability Test on Blended Cement and Other Concretes: Correlations Between Charge, Initial Current and Conductivity," *Construction and Building Materials*, V. 13, 1999, pp. 149-154.
8. Stanish, K. D.; Hooton, R. D.; and Thomas, M. D. A., "Testing the Chloride Penetration Resistance of Concrete: A Literature Review," FHWA Contract DTFH61-97-R-00022, University of Toronto, Toronto, ON, Canada, June 2000, 31 pp.
9. Scali, M. J.; Chin, D.; and Berke, N. S., "Effect of Microsilica and Fly Ash Upon the Microstructure and Permeability of Concrete," *Proceedings of the Ninth International Conference on Cement Microscopy*, Reno, NV, Apr. 5-9, 1987, pp. 375-397.
10. Feldman, R.; Chan, G.; Brouseau, R.; and Tumidajski, P., "An Investigation of the Rapid Chloride Permeability Test," *Proceedings of the Third Canadian Symposium on Cement and Concrete*, Ottawa, ON, Canada, Aug. 3-4, 1993, pp. 279-306.
11. Zhao, T. J.; Zhou, Z. H.; Zhu, J. Q.; and Feng, N. Q., "An Alternating Test Method for Concrete Permeability," *Cement and Concrete Research*, V. 28, No. 1, 1998, pp. 7-12.
12. ASTM C1556, "Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion," ASTM International, West Conshohocken, PA, 2004, 7 pp.
13. ASTM C494, "Standard Specification for Chemical Admixtures for Concrete," ASTM International, West Conshohocken, PA, 1999, 9 pp.
14. ASTM C618, "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete," ASTM International, West Conshohocken, PA, 2003, 3 pp.
15. ASTM C989, "Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars," ASTM International, West Conshohocken, PA, 2005, 5 pp.