

Tests and Criteria for Concrete Resistant to Chloride Ion Penetration

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This paper presents a portion of a state highway agency pooled fund research project to develop performance criteria for concrete that will be resistant to penetration of chlorides, cycles of freezing and thawing, and sulfate attack. This paper presents the portion of the study pertaining to penetration of chlorides. To simulate standard and service conditions, specimens were subjected to either immersion or to a cyclic wetting and drying exposure in chloride solution. Measured apparent chloride diffusion coefficients, determined in accordance with ASTM C1556, were correlated with results of rapid index test methods that provide an indication of the transport characteristics of concrete. Rapid index test methods included were rapid chloride permeability, rapid migration, conductivity, absorption, and initial and secondary sorptivity. A set of rapid index test methods and specification criteria that can reliably classify mixtures based on their resistance to chloride ion penetration are proposed.

Keywords: ACI 318; building code; chloride; corrosion resistance; diffusivity; performance-based specifications; permeability; pore solution conductivity; sorptivity.

INTRODUCTION

A review of national codes and specifications revealed that while performance criteria were used for some properties of concrete, durability was typically specified with prescriptive provisions (Bickley et al. 2006). These prescriptive provisions typically include the use of specific materials, maximum water-cementitious materials ratio (w/cm), minimum cement factors, and limits on supplementary cementitious materials. There is considerable interest in evolving towards performance-based specifications, in public and private work (FHWA-RD 1999; P2P Initiative 2009; ACI 329R-14; Bickley et al. 2006). A challenge with implementing performance-based specifications, especially for improved durability, is the selection of appropriate test methods and specification criteria that can reliably provide the expected service life in the anticipated service conditions.

Corrosion of steel is the primary cause of deterioration of reinforced concrete. The main reason is the ingress of chlorides from deicing salts or exposure to marine environment. Carbonation is another factor. Concrete that resists the ingress of chlorides will generally not be susceptible to carbonation-related corrosion with adequate cover. Initiation of reinforcement corrosion occurs when chloride ion concentration at the steel exceeds a threshold level. Initiation of corrosion can be delayed by providing adequate cover to reinforcement and using concrete with a low permeability (Broomfield 1997; Bentur et al. 1998). Use of corrosion inhibitors and alternative types of steel are other methods to

minimize deterioration of concrete structures due to corrosion (Berke and Rosenberg 1989; Nmai et al. 1992).

The apparent chloride diffusion coefficient (D_a) of concrete, measured in accordance with ASTM C1556, has been widely used in service life prediction of reinforced concrete exposed to chlorides (ACI 365.1R-00; Thomas and Jones 1996; Life-365 2009). This is an involved test method, and useful in research, but not conducive to pre-qualification and acceptance of concrete mixtures on projects. The purpose of this study was to evaluate several rapid index tests that simulate the transport characteristics of concrete and to recommend criteria that correlate well with the measured D_a . These index tests and criteria can then be used to select mixtures of the desired chloride penetrability level within a testing period of approximately 56 days.

In concrete that is close to a saturated condition, chloride ingress occurs by diffusion. This is applicable for structures in a submerged marine exposure, in contact with ground, or exterior structural members in regions of higher precipitation and high humidity. In concrete that is in an unsaturated condition, chloride ingress occurs by a combination of absorption and diffusion. To simulate the chloride ingress in these different service conditions, specimens were subjected to immersion in chloride solution and to a cyclic wetting and drying exposure in a chloride solution.

RESEARCH SIGNIFICANCE

This paper proposes rapid index tests and specification criteria that can reliably classify concrete mixtures for resistance to chloride penetration within a testing period of approximately 56 days. Based on this research, alternative performance-based criteria to the prescriptive w/cm requirement for exposure class C2 in the ACI 318 Building Code are proposed. This proposed change supports the evolution to performance-based specification.

LITERATURE REVIEW

Garboczi (1990) and Martys (1995) discuss the fundamental mechanisms that involve transport of fluid and chemical species in cementitious systems and types of measurements that can be used to characterize transport properties. Stanish et al. (1997) discuss the mechanisms of chloride

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penetration and the characteristics of concrete mixtures that impact chloride penetrability. They discuss longer-term chloride diffusion tests, as well as shorter-term electrical and sorption-based test methods to evaluate concrete mixtures with different w/cm and cementitious material composition. A comprehensive evaluation of test methods was also reported in Europe (RILEM TC 116 1989; RILEM TC 189 2008). The South African Durability Index was established based on gas permeability, chloride ingress, and water penetrability measurements (Beushausen and Alexander 2008).

A commonly used test method for concrete mixture evaluation for chloride penetration in the United States is the “Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration” (ASTM C1202; AASHTO T 277), commonly referred to as the rapid chloride permeability test (RCPT). This test was developed in the 1980s (Whiting 1981; Whiting and Mitchell 1992). The test measures the charge passed through a saturated concrete specimen with the application of an electrical potential. A lower charge passed is assumed to provide an indication of better resistance to penetration of chloride ions. In essence, the test method measures the conductivity of concrete. As originally developed, the intent was to establish a correlation of the charge passed measured by ASTM C1202 with the depth of chloride penetration in the chloride ponding test (AASHTO T 259; ASTM C1543). The conductivity of the concrete is related to its diffusivity through the Nernst-Einstein equation (Shane et al. 1997) as follows:

$$\frac{\sigma}{\sigma_o} = \frac{D}{D_o} = FF \quad (1)$$

where σ is overall bulk conductivity of concrete; σ_o is pore solution conductivity; D is diffusivity of chloride ion in concrete; D_o is intrinsic diffusivity of chloride ion in pore solution; and FF is formation factor, which is a function of porosity and pore connectivity in concrete.

The intrinsic diffusivity of chloride ions in solution, D_o , changes by approximately 15% from pure water to that in a concentrated solution (0.5 molar) that is typical of the pore solution in concrete (Shane et al. 1997). Pore solution conductivity σ_o does vary in different concrete mixtures and can be measured by expressing the pore fluid from the hardened concrete or estimated based on chemical composition of the cementitious materials (Snyder et al. 2003; NIST 2015). The formation factor thereby gets closer to characterizing the transport property of concrete as an intrinsic material property. Electrical measurements facilitate the estimation of the formation factor.

There have been several evaluations on whether ASTM C1202 provides a reliable indicator of the transport characteristics of concrete and whether it can be used to estimate the diffusion coefficient of concrete for service life modeling (Feldman et al. 1994; Mobasher and Mitchell 1988). In some work, concrete mixtures with low RCPT results (coulombs) had a high effective diffusion coefficient (Mackechnie and Alexander 2000). Results from chloride ponding tests (AASHTO T 259) have also been shown to not always

correlate well with the ASTM C1202 test results (Scanlon and Sherman 1996; Pfeifer et al. 1994). The pore solution conductivity of the concrete is a function of the ionic concentration that is impacted by the use of pozzolanic materials and slag cement or certain admixtures, such as calcium nitrite. Specifically, it is reported that the use of silica fume strongly influences the pore solution conductivity (Shi et al. 1998; Liu and Beaudoin 2000; López and Gonzalez 1993). Hence, research has demonstrated that ASTM C1202 results can provide a false indication of the transport characteristics of concrete mixtures for some types of concrete mixtures. For this reason, it has been suggested that ASTM C1202 results be validated with chloride ponding tests for the specific concrete mixtures prior to its use as a specification criterion. Other research studies indicate reasonable confidence with using ASTM C1202, provided the concrete mixtures are cured for a longer period or accelerated curing is used so that the contribution of the supplementary cementitious materials (SCMs) to the beneficial performance of concrete can be realized (Ozyildirim and Halstead 1988; Plauto and Bilodeau 1989). Various improvements to ASTM C1202 have been suggested (Feldman et al. 1994) to improve the reliability of the method, including saturating the specimens in a sodium chloride solution to minimize the impact of pore solution on the measured result (Streicher and Alexander 1995).

Other electrical measurements on concrete have been developed by researchers (Tang 1996; Stanish et al. 2004; Riding et al. 2008). The electrical conductivity of concrete can be measured on concrete using the same equipment used for ASTM C1202 and this method has been standardized (ASTM C1760). Surface or bulk resistivity (inverse of conductivity) of concrete using the Wenner Probe is another electrical measurement that can be performed rapidly and, with appropriate corrections, reliable results indicating the transport characteristics of concrete can be obtained (Presuel-Moreno et al. 2009; Rupnow and Icenogle 2011; Spragg et al. 2011).

MATERIALS AND MIXTURE PROPORTIONS

The following materials were used for the concrete mixtures:

- ASTM C150 Type I portland cement (PC);
- ASTM C618 Class F fly ash (FA);
- ASTM C989 slag cement (SL);
- ASTM C1240 silica fume (SF);
- ASTM C33 No. 57 crushed coarse aggregate;
- ASTM C33 natural sand with a fineness modulus = 2.88; and
- ASTM C494 Type A and F water-reducing chemical admixtures.

The following were considerations when establishing concrete mixtures parameters for this study:

1. w/cm and SCM quantities were chosen to cover the ranges typically used in high-performance concrete. These parameters were varied to ensure that the range of measured results from the rapid index tests could reliably classify mixtures for transport characteristics.

2. Mixture parameters were varied to achieve a broad range of apparent chloride diffusion coefficient, D_a . The 2-year predicted D_a based on the Life-365 service life model for

concrete exposed to chlorides for the different mixture compositions varied between 6.8×10^{-12} and 0.62×10^{-12} m²/s.

3. Additionally, mixtures with high w/cm and high SCM quantities, as well as with very low w/cm and no SCM, were prepared. Mixtures with high w/cm and high SCM content are known to yield low RCPT values due to their low pore solution conductivity. However, increasing the w/cm is generally expected to increase the diffusivity of the mixtures, so the question was whether rapid index tests can reliably classify mixtures according to the measured D_a for such mixtures.

The 13 non air-entrained concrete mixtures were evaluated in two phases of this study. Mixture designations were assigned by the w/cm followed by the SCM type and quantity. For example 0.49SL25 referred to mixture with a w/cm of 0.49 and 25% slag cement. Mixtures without SCM use the designation "PC." The mixture proportions and test results of the six mixtures evaluated in Phase I are provided in Table 1. Details of the seven mixtures evaluated in Phase II are provided in Table 2. The pore solution conductivity of the various mixtures were estimated using an online model (NIST 2015) based on the composition of the cementitious materials and reported in Tables 1 and 2. These values varied over a wide range of 3.36 to 17.09 Siemens/m.

CURING AND TESTING PROCEDURES

Concrete mixtures were mixed in a revolving drum laboratory mixer in accordance with ASTM C192. The water reducing admixture dosage was adjusted to attain a target slump of 5 to 7 in. (125 to 175 mm) for the concrete mixtures tested. Fresh concrete was tested for slump (ASTM C143), temperature (ASTM C1064), air content (ASTM C231), and density (ASTM C138).

The hardened concrete specimens were subject to two types of curing:

1. Standard curing when specimens were stored in a moist room at $73 \pm 3^\circ\text{F}$ ($23 \pm 2^\circ\text{C}$) immediately after casting the specimens and for the duration prior to testing.

2. Accelerated curing when specimens were subjected to 7 days of standard curing followed by 21 days of curing in lime-saturated water at 100°F (38°C). The accelerated most curing procedure is defined in ASTM C1202 and has been shown to provide an earlier indication of potential property development with slower hydrating supplementary cementitious materials (Ozyildirim 1998).

Tests on hardened concrete included compressive strength (ASTM C39) on two 4 x 8 in. (100 x 200 mm) cylindrical specimens standard cured and tested at an age of 28 days. Length change as an indication of drying shrinkage (ASTM C157) was determined using three 3 x 3 x 11-1/4 in. (75 x 75 x 285 mm) prisms, with 7 days standard curing followed by up to 180 days of air drying in a 70°F (21°C), 50% RH environment.

Rapid index tests to measure the transport characteristics of concretes included the RCPT (ASTM C1202), rapid migration test (RMT) (AASHTO TP 64), conductivity, absorption, and initial and secondary sorptivity (ASTM C1585). These tests were conducted at an age of 28 days using the accelerated curing procedure and at an age of 56 days following standard curing. The results for these rapid index tests are

the average of two 4 x 8 in. (100 x 200 mm) cylindrical specimens for each test age and curing condition. The specimens were cut and the top 2 in. (50 mm) from the finished surface were tested.

The RCPT, RMT, and conductivity tests are electrical tests. The ratio of the RCPT and the estimated pore solution conductivity (RCPT/PSC) are also reported for the different mixtures. The absorption and sorptivity tests were performed to provide supporting information for the ingress of chlorides determined for specimens subjected to cyclic wetting and drying.

The conductivity test performed differs from the recently standardized ASTM C1760. The method performed was similar to the RCPT with the exception that a 0.3N sodium hydroxide solution was used on both sides of the specimen with an applied voltage of 60 V. The test was performed for five minutes after which the current (I) was recorded.

The conductivity σ , in S/m (Siemens/meter), was calculated as follows

$$\sigma = \frac{I \times L}{V \times A} \quad (2)$$

where V is applied voltage, volts; I is measured current, amps; A is specimen cross-sectional area, mm²; and L is specimen length, mm.

The absorption test used in this study was based on BS 1881-122. It involved oven drying the specimen for 72 ± 2 hours followed by cooling for 24 ± 0.5 hours in a dry, air-tight vessel. The specimen was immersed in water for 30 ± 0.5 minutes and the quantity of water absorbed by the specimen was determined. Absorption is calculated as a percent increase in mass from the dried condition. For Phase I, the specimens were dried at 220°F (105°C). For Phase II, the specimens were dried at 140°F (60°C) because it was felt that the high temperature used in Phase I may cause internal micro-cracking of concrete that could increase the measured absorption of the concrete specimen being tested.

Testing to measure D_a , in accordance with ASTM C1556, involved casting two 4 x 8 in. (100 x 200 mm) cylindrical specimens. After varying periods of standard curing, the specimens were cut at 3 in. (75 mm) from the finished surface. The circumference and cut end of the specimens were coated with an epoxy and the specimens were immersed in an aqueous solution of sodium chloride. Chloride ingress occurs from the finished surface of the specimen. Specimens for measuring the apparent chloride diffusion coefficient D_a in accordance with ASTM C1556 were subjected to the following conditioning:

Phase I—

- i) 59 days standard curing + 16 months in chloride solution (referred to as "Phase I Immersed"); and

- ii) 59 days standard curing + cyclic wet/dry exposure to chloride solution for 4 months. This involved 4 days immersion in chloride solution and 3 days drying at 100°F (38°C) air at 20% RH (referred to as "Phase I Cyclic").

Phase II—

- i) 6 months standard curing + 15 months in chloride solution (referred to as "Phase II Immersed"); and

Table 1—Yield-adjusted mixture composition and test results (Phase I)

	0.49PC	0.49SL25	0.39SL50	0.49FA15	0.39FA30	0.34SL40SF5
Calculated batch quantities						
Type I/II cement, lb/yd ³	554	416	306	472	431	382
Slag cement, lb/yd ³	—	139	306	—	—	277
Fly ash, lb/yd ³	—	—	—	83	185	—
Silica fume, lb/yd ³	—	—	—	—	—	35
Total cementitious content, lb/yd ³	554	555	612	555	616	694
SCM, %	0	25	50	15	30	45
w/cm	0.49	0.49	0.39	0.49	0.39	0.34
ASTM C494 Type A, oz/cwt	4.0	4.0	4.0	4.0	4.0	4.0
ASTM C494 Type F, oz/cwt	2.5	2.9	4.3	2.4	5.0	7.8
Estimated PSC, S/m*	7.9	6.1	5.8	7.93	11	7.78
Fresh concrete properties						
ASTM C143, slump, in.	7.5	4.5	8	7	6.75	9
ASTM C231, air, %	1.4	1.7	1.3	1.5	1.6	1
ASTM C138, density, lb/ft ³	156.5	156.1	157.7	155.7	156.5	159.3
ASTM C1064, temperature, °F (°C)	76 (24.5)	76 (24.5)	75 (24)	76 (24.5)	75 (24.5)	75 (24)
Hardened concrete properties						
ASTM C39, compressive strength, psi						
28 days	6830	7550	10,520	6640	7970	12,440
Water absorption test (drying at 221°F [105°C]), % change in mass						
10-day standard cure	2.89	2.24	1.69	3.25	2.33	1.43
28-day accelerated cure	2.52	1.77	1.34	2.44	1.63	1.26
ASTM C1202, rapid chloride permeability, coulombs						
28-day accelerated cure	4657	1992	561	2414	723	166
56-day standard cure	4674	1912	581	3013	1417	270
28-day RCPT/PSC	589	327	97	304	66	21
56-day RCPT/PSC	592	313	100	380	129	35
Conductivity, Sm ⁻¹						
28-day accelerated cure	0.0189	0.0083	0.0030	0.0091	0.0030	0.0009
56-day standard cure	0.0154	0.0072	0.0034	0.0129	0.0058	0.0013
AASHTO TP 64, rate of penetration, mm/(V-h)						
28-day accelerated cure	0.065	0.030	0.004	0.046	0.015	0.003
56-day standard cure	0.044	0.025	0.006	0.043	0.024	0.002
ASTM C157, length change, %						
28 days drying	0.035	0.039	0.031	0.029	0.028	0.028
ASTM C1585, rate of water absorption (initial/secondary sorptivity), × 10 ⁻⁴ mm/s ^{1/2}						
28-day accelerated cure	10.4/7.5	3.0/3.4	1.7/1.7	7.5/4.6	4.7/2.1	2.5/0.9
56-day standard cure	9.9/6.9	8.5/2.6	2.5/1.4	16.6/10.7	7.0/3.3	4.1/1.9
ASTM C1556, apparent chloride diffusion coefficient D_a , × 10 ⁻¹² m ² /s						
Phase I Immersed	12.94	3.09	0.58	4.11	1.07	0.35
Phase I Cyclic	11.07	3.11	1.24	6.34	3.42	0.82

*PSC is pore solution conductivity estimated from NIST model (NIST 2015).

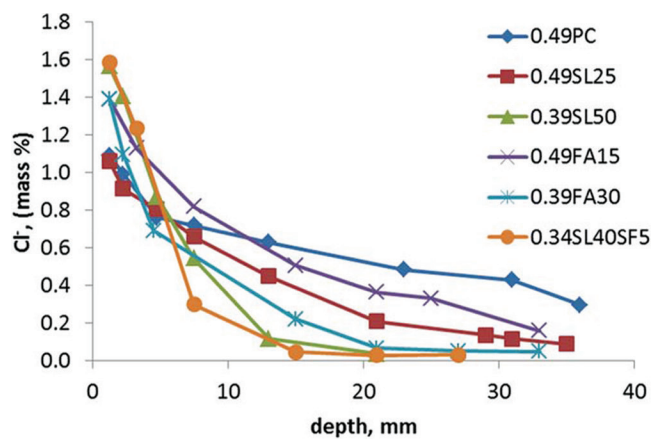
Notes: 1 lb/yd³ = 0.5933 kg/m³; 1 oz/cwt = 65.3 mL/100 kg; 1 in. = 25 mm; 1 lb/ft³ = 16.02 kg/m³; 1 psi = 0.0069 MPa.

Table 2—Yield-adjusted mixture proportions and test results (Phase II)

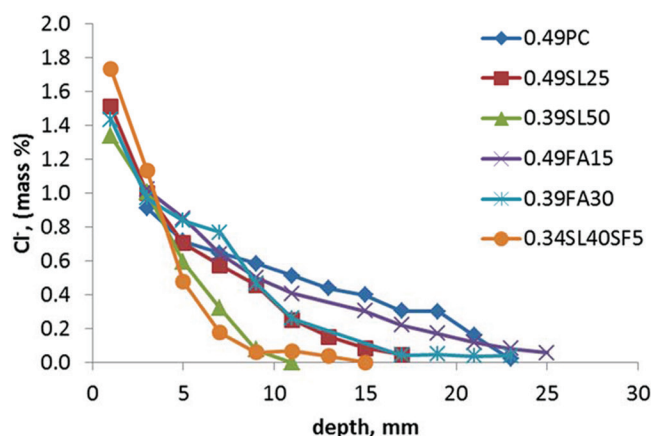
	0.39PC	0.39FA15	0.39SL25	0.39SF7	0.62FA30	0.62SL50	0.29PC
Calculated batch quantities							
Type I/II cement, lb/yd ³	612	520	462	565	349	249	803
Slag cement, lb/yd ³	—	—	154	—	—	249	—
Fly ash, lb/yd ³	—	92	—	—	149	—	—
Silica fume, lb/yd ³	—	—	—	43	—	—	—
Total cementitious content, lb/yd ³	612	612	616	608	498	498	803
SCM, %	0%	15%	25%	7%	30%	50%	0%
w/cm	0.39	0.39	0.39	0.39	0.62	0.62	0.29
ASTM C494 Type A, oz/cwt	4	4	4	4	3	3	5
ASTM C494 Type F, oz/cwt	8.8	8.3	6.9	8.2	—	—	11.7
Estimated PSC, S/m*	10.9	10.9	8.4	9.3	6.5	3.4	17.1
Fresh concrete properties							
ASTM C143, slump, in.	5	6 1/2	7 3/4	6	6 1/2	7	8 3/4
ASTM C231, air, %	1.8	1.6	1.2	1.8	1.6	1.4	1.1
ASTM C138, density, lb/ft ³	158.1	156.9	158.9	156.5	152.5	154.1	159.7
ASTM C1064, temperature, °F (°C)	75 (24)	75 (24)	75 (24)	75 (24)	75 (24)	75 (24)	76 (24.5)
Hardened concrete properties							
ASTM C39, compressive strength, psi							
28 days	10,460	9,590	10,300	10,740	3,880	5,380	13,480
Water absorption test (drying at 140°F [60°C]), % change in mass							
56-day standard cure	1.03	1.02	1.00	0.82	1.88	1.75	0.91
213-day standard cure	0.85	0.79	0.91	0.76	1.55	1.40	0.70
ASTM C1202, rapid chloride permeability, coulombs							
28-day accelerated cure	1980	1031	1186	276	2495	661	1078
56-day standard cure	1722	1557	1272	299	4012	832	1209
28-day RCPT/PSC	182	95	141	30	382	197	63
56-day RCPT/PSC	158	143	151	32	614	248	71
Conductivity, Sm ⁻¹							
28-day accelerated cure	0.0102	0.0054	0.0061	0.0014	0.0089	0.0037	0.0061
56-day standard cure	0.0089	0.0070	0.0058	0.0014	0.0119	0.0034	0.0056
AASHTO TP 64, rate of penetration, mm/(V-h)							
28-day accelerated cure	0.029	0.017	0.013	0.004	0.047	0.007	0.012
56-day standard cure	0.027	0.017	0.011	0.004	0.046	0.012	0.011
ASTM C157, length change, %							
28 days drying	0.032	0.037	0.032	0.028	0.041	0.044	0.024
ASTM C1585, rate of water absorption (initial/secondary sorptivity), × 10 ⁻⁴ mm/s ^{1/2}							
28-day accelerated cure	9.5/5.2	3.1/2.1	4.7/2.0	3.3/2.1	9.6/3.8	7.6/2.8	3.1/2.6
56-day standard cure	8.3/4.0	6.1/4.1	Unavailable	3.8/2.1	9.9/7.0	7.1/2.8	2.1/2.9
ASTM C1556, apparent chloride diffusion coefficient D_a , × 10 ⁻¹² m ² /s							
Phase II Immersed	1.75	0.67	0.77	0.22	0.95	0.55	0.56
Phase II Cyclic	1.96	0.94	0.42	0.35	7.10	1.45	0.53

*PSC is pore solution conductivity estimated from NIST model (NIST 2015).

Notes: 1 lb/yd³ = 0.5933 kg/m³; 1 oz/cwt = 65.3 mL/100 kg; 1 in. = 25 mm, 1 lb/ft³ = 16.02 kg/m³; 1 psi = 0.0069 MPa.



(a)



(b)

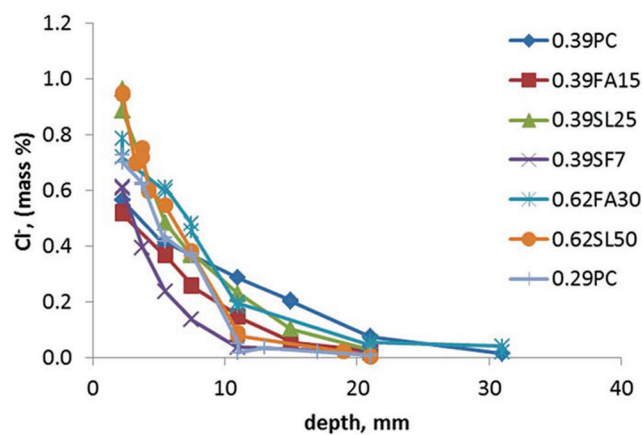
Fig. 1—Chloride profile for Phase I conditions: (a) immersed; and (b) cyclic. (Note: 1 mm = 0.039 in.)

ii) 56 days standard curing + cyclic wet/dry exposure to chloride solution for 18 months. This involved 3 days immersion in chloride solution and 4 days drying at 73°F (23°C) air at 50% RH (referred to as “Phase II Cyclic”).

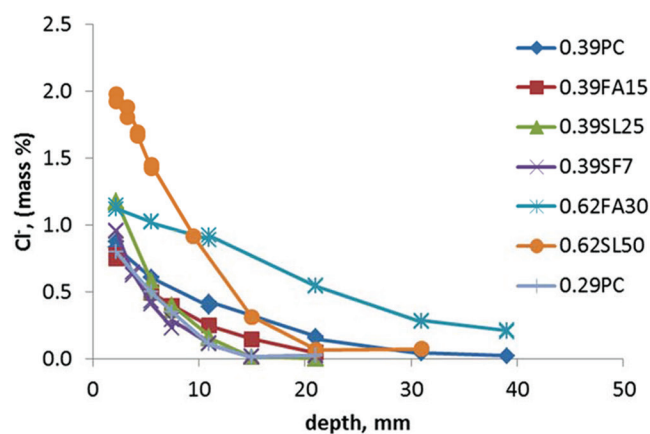
For the Phase I mixtures, the chloride profiles of specimens subjected to immersion or cyclic wet/dry exposure to chloride solution are plotted in Fig. 1. The calculated apparent chloride coefficient for these mixtures are reported in Table 1.

For the Phase II mixtures, the chloride profiles of specimens subjected to immersion or cyclic wet/dry exposure to chloride solution are plotted in Fig. 2. The calculated apparent chloride coefficient for these mixtures are reported in Table 2.

It is recognized that chloride ingress in the specimens subjected to cyclic wetting and drying is a combination of absorption and diffusion. Additionally, it is expected that during the drying phase, there will be movement of moisture and chlorides from the interior saturated zone to the exterior drier zones. It is recognized that the computed D_a for specimens subject to cyclic wetting and drying are not representative of diffusion mechanisms but were calculated from the chloride ingress profiles and reported to get an estimate of chloride penetration and to provide a basis for comparison



(a)



(b)

Fig. 2—Chloride profile for Phase II conditions: (a) immersed; and (b) cyclic. (Note: 1 mm = 0.039 in.)

of chloride ingress in saturated specimens. Chloride ingress into unsaturated concrete has been modeled in other research studies (Bastidas-Arteaga et al. 2011; Saetta et al. 1993; Ababneh et al. 2003).

CHLORIDE PROFILES AND APPARENT CHLORIDE DIFFUSION COEFFICIENT

The D_a values of specimens subject to the immersed condition are generally similar to those subject to the cyclic condition. Exception to this is observed for two mixtures with a 0.62 w/cm. The two mixtures with a 0.62 w/cm had significantly lower D_a values in the immersed condition compared to the cyclic wetting and drying condition, suggesting better performance for the saturated specimens. On the other hand, based on the D_a values, it appears that mixtures with a lower w/cm performed better in the cyclic condition due to the tighter pore structure at the concrete surface and difference in drying rates.

There is at least one order of magnitude difference in the range of the D_a values for the different mixtures evaluated. This illustrates the broad range of D_a values for concrete mixtures possible with the materials and mixture proportions commonly used.

Table 3—Correlation between rapid index and apparent chloride D_a test results

Rapid index test	Coefficient of determination R^2 with apparent chloride D_a	
	Average for immersed	Average for cyclic
Conductivity	0.88	0.78
RCPT (ASTM C1202)	0.76	0.93
RMT (AASHTO TP 64)	0.62	0.85
RCPT/PSC	0.55	0.92
Absorption	NA	0.63
Initial sorptivity (ASTM C1585)	0.65	0.74
Secondary sorptivity (ASTM C1585)	0.86	0.71

CORRELATING APPARENT DIFFUSION COEFFICIENT AND RAPID INDEX TEST RESULTS

The coefficient of determination (R^2) of the linear correlations between each of the rapid index test results and the calculated apparent chloride D_a are summarized in Table 3. The RCPT values of the mixtures were divided by their estimated pore solution conductivities (PSC) and the resulting factor was also correlated with the D_a . This was done to see if normalizing the RCPT result by the pore solution conductivity would yield a better correlation as suggested by the Nernst-Einstein equation discussed earlier. An R^2 value of 1 indicates a perfect linear correlation.

For D_a calculated on specimens in the immersed condition, the 28-day accelerated cured rapid index test results had a better correlation as indicated by the higher R^2 values. For D_a measured on specimens in the cyclic condition, in general, the 56-day standard cured rapid index test results had a better correlation—that is, higher R^2 values. The actual R^2 values for the different ages as well as the different phases are reported elsewhere (Obla et al. 2015).

Overall, conductivity and RCPT test results had the best correlation to the calculated D_a values, with R^2 values exceeding 0.80. A lower R^2 value was typically evident when results of one mixture substantially deviated from the line of correlation. The other rapid index tests did not show a strong correlation with D_a values. Normalizing the RCPT results by the pore solution conductivity (RCPT/PSC) did not improve the correlation with calculated D_a .

MIXTURE CLASSIFICATION FOR CHLORIDE PENETRABILITY

The apparent chloride diffusion coefficient D_a varied over a wide range with the varying mixtures, curing and specimen conditioning used. To facilitate comparison of the different conditions, the D_a was normalized by dividing each mixture's D_a by the average D_a for all the mixtures tested in that Phase and condition. For example, all Phase I immersed D_a values were divided by the average value. The resulting value for each mixture is referred to as the normalized apparent chloride diffusion coefficient (ND_a). This parameter has no physical significance but is used as a means to

Table 4—Chloride penetrability level for test criteria

Chloride penetrability level	ND_a	RCPT, coulombs	RMT, mm/(V-h)	Conductivity, S/m	Secondary sorptivity, $\times 10^{-4}$ mm/s ^{0.5}
Very Low	≤ 0.4	≤ 1000	≤ 0.012	≤ 0.0045	≤ 2.20
Low	0.4 to 1.0	1000 to 2000	0.012 to 0.024	0.0045 to 0.0084	2.20 to 4.40
Moderate	≥ 1.0	≥ 2000	≥ 0.024	≥ 0.0084	≥ 4.40

categorize mixtures based on their chloride penetrability, as follows:

- “Very Low” when $ND_a \leq 0.4$;
- “Low” when $0.4 < ND_a < 1.0$; and
- “Moderate” when $ND_a \geq 1.0$.

Chloride penetrability criteria for rapid index test related to these categories are suggested in Table 4. The chloride penetrability performance of the different mixtures in this study were then categorized based on the ND_a and rapid index test results. When the performance category from a rapid index test matched that from the ND_a , it is suggested that the rapid index test is effective for categorizing the performance of the mixture for chloride penetrability. Figure 3 illustrates mixture classification based on RCPT results and the ND_a . Similar charts were developed for conductivity, RMT, absorption, initial sorptivity, secondary sorptivity tests, and RCPT/PSC and are reported elsewhere (Obla et al. 2015).

Figure 3 illustrates that mixture classification based on the RCPT results generally matched the classification for the proposed levels of performance based on ND_a . Figures 3(c) and (d) indicate that the RCPT classifies the 0.62SL50 mixture as “Very Low” chloride penetrability, whereas the ND_a classified that mixture as “Low.” The classification in Fig. 3(d) (Phase II cyclic) appears to further deviate from a linear correlation. The 56-day standard cured RCPT result (832 coulombs) for the 0.62SL50 mixture was lower than that for the 0.39SL25, 0.29PC, and 0.39FA15 mixture (1200 to 1600 coulombs). But the D_a value for the 0.62SL50 mixture was 1.5 to 3.5 times higher than those mixtures. In Fig. 3(c) (Phase II immersed), even though the 28-day accelerated cured RCPT result (661 coulombs) for the 0.62SL50 mixture was lower than that for the 0.39SL25, 0.29PC, and 0.39FA15 mixture (about 1100 coulombs), the D_a for all the mixtures were similar. Similar observations were made for the conductivity and RMT results as well. This illustrates that the electrical-based measurements can provide a false indication of the chloride penetrability property. The sorptivity test results in Table 2 provide some possible reasons for the potential discrepancy. The 56-day initial sorptivity for the 0.62SL50 mixture was significantly higher than that of the other mixtures, indicating that there is a higher rate of transport due to the higher w/cm of this mixture, which is an important factor particularly for the cyclic condition. For this mixture, when the RCPT result was normalized to the estimated pore solution conductivity (RCPT/PSC), the classification of this mixture changed to a performance category with higher chloride penetrability. However, because the

Table 5—Mixtures categorized by ND_a and (RCPT + strength) for chloride penetrability

Chloride penetrability level	ND_a	RCPT, coulombs	28-day compressive strength, psi (MPa)	Mixtures*	Mixtures†
Very low	≤ 0.4	≤ 1000	≥ 5700 (40)	0.34SL40SF5, 0.39SF7, 0.39SL50, 0.39FA30	0.34SL40SF5, 0.39SF7, 0.39SL50
Low	0.4 to 1.0	1000 to 2000	≥ 3200 (22)	0.29PC, 0.39FA15, 0.39SL25, 0.62SL50	0.29PC, 0.39FA15, 0.39SL25, 0.39PC, 0.62SL50, 0.39FA30, 0.49SL25
Moderate	≥ 1.0	> 2000	≥ 3200 (22)	0.49FA15, 0.49PC, 0.39PC, 0.49SL25, 0.62FA30	0.62FA30, 0.49PC, 0.49FA15

* D_a measured on specimens immersed condition (Phase I+II); RCPT accelerated cure for 28 days.

† D_a measured on specimens with cyclic condition (Phase I+II); RCPT standard cure for 56 days.

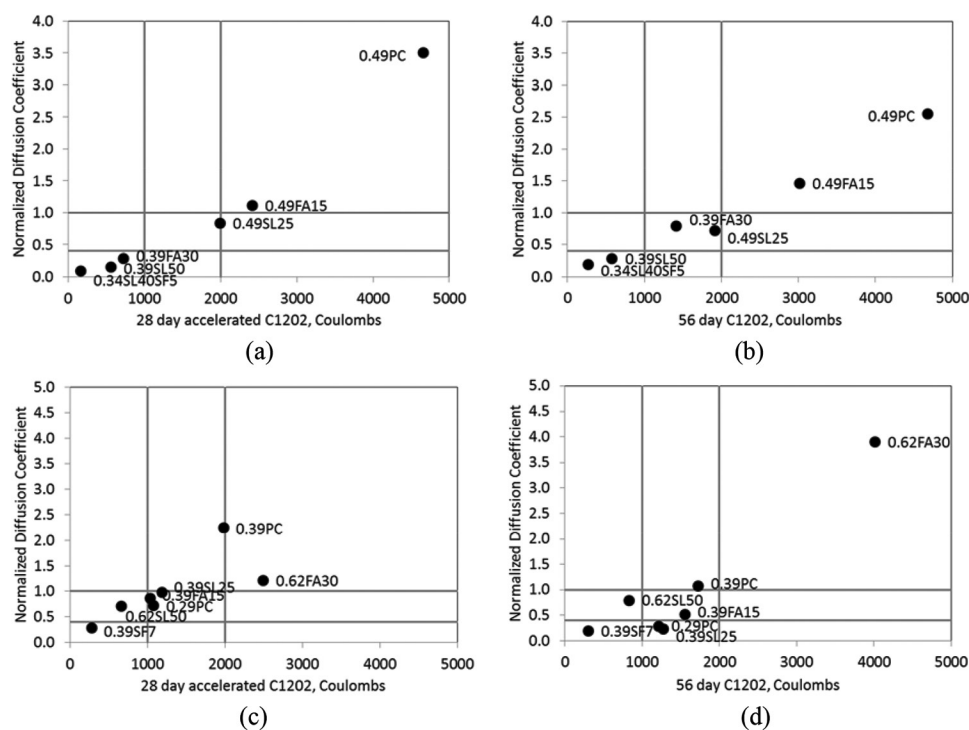


Fig. 3—Correlation between RCPT and normalized apparent chloride diffusion coefficients (ND_a): (a) Phase I Immersed; (b) Phase I Cyclic; (c) Phase II Immersed; and (d) Phase II Cyclic.

RCPT/PSC normalization did not improve the correlation with ND_a for all mixtures, this approach was not pursued.

Fly ash tends to react slowly and therefore the RCPT results of the 0.62FA30 mixture in Phase II indicate a high chloride ion penetration, consistent with expectations.

From Fig. 3(d), it can be observed that the RCPT result for the 0.39SF7 mixture that was standard cured for 56 days was much lower than that for the 0.39SL25 and 0.29PC mixtures. However, the cyclic D_a values for all three mixtures were similar. This indicates that silica fume is more effective in achieving a lower RCPT result that is not reflected in reduction in the D_a value for the cyclic case. However, for specimens subjected to the immersed condition (Fig. 3(c)) the RCPT test seems to be a good indicator for the same set of mixtures.

The data reveal that depending solely on the RCPT or conductivity tests can provide a false indication of chloride penetrability for some types of mixtures. Specifically, high w/cm mixtures containing slag cement or silica fume can have lower RCPT values that are not consistent with

the transport characteristics of the concrete as indicated by the apparent chloride diffusion coefficient. It is thereby suggested that, despite the generally good correlation of the RCPT, some supplementary performance criterion that validates this performance may be required.

USING A COMBINATION OF RAPID INDEX TESTS

Currently, in ACI 318, the reliance for reduced permeability is based on a maximum w/cm . As indicated in this study, mixtures at the same w/cm will have different levels of permeability. In evolving to a performance test, such as ASTM C1202, there are some situations where a false indication is possible with mixtures at a higher w/cm . Therefore, a combination of tests and criteria is necessary. In considering more than one rapid index test, the intent is to ensure that the combination of the criteria provide reasonable assurance of achieving concrete with the desired level of chloride penetrability. A secondary factor is that the tests selected should be easy to perform within a 56-day window and provide reliable results. Table 5 suggests compres-

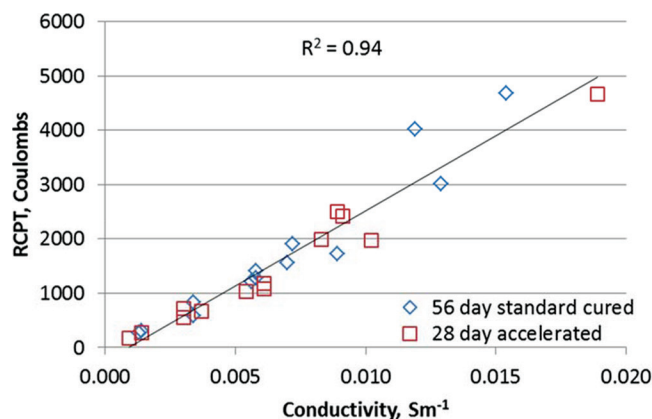


Fig. 4—Correlation between RCPT and conductivity.

sive strength as a rapid index test to supplement the RCPT criteria. When strength and RCPT results categorized a mixture in two different chloride penetrability levels, that mixture was conservatively classified as belonging to the higher chloride penetrability level. Using these two index tests, all of the mixtures in this study were re-classified in Table 5. In Table 5, the mixture categorization based on the RCPT and strength criteria matches the performance levels as categorized by the ND_a value.

The value in using two rapid index criteria—strength and RCPT—is observed for the 0.62SL50 mixture. Using both results this mixture is placed in the “Low” category. However, mixtures 0.29PC and 0.39SL25 are still placed in the Low category even though they had “Very low” D_a . Nevertheless, the combined RCPT and strength criteria are conservative and appropriately categorize the mixture with slag cement with a high w/cm .

The RCPT and conductivity test results for all the mixtures are plotted in Fig. 4. The results indicate a good correlation suggesting that a simpler conductivity test such as ASTM C1760 could be used as an alternative to ASTM C1202. It is also anticipated that a resistivity test that is being standardized by ASTM would also be a good alternative to ASTM C1202.

The suggested performance criteria were evaluated for 30 additional concrete mixtures with varying w/cm , SCM dosages and cement types from the broader pooled fund research project. RCPT, strength, and sorptivity were measured for those mixtures. Mixtures were classified in the chloride penetrability categories based on the measured rapid index test results and the adequacy of the classification was evaluated by comparing against the chloride penetrability levels of similar mixtures reported in Table 1 and 2. Based on this analysis (Obla et al. 2015), the performance tests and criteria for resistance to chloride penetrability were modified slightly and are discussed in the following.

SUGGESTED PERFORMANCE CRITERIA FOR CONCRETE RESISTANT TO CHLORIDE ION PENETRATION

The proposed performance tests and criteria for chloride exposure are shown in Table 6. The specified strength levels are determined to the nearest 500 psi (3.5 MPa) from the

Table 6—Suggested tests and specification criteria for chloride penetrability

Chloride penetrability level	Specified RCPT, coulombs	Specified compressive strength* at 28 days, psi (MPa)
Very low	≤ 1000	≥ 5000 (35)
Low	1000 to 2500	≥ 4000 (28)

*These strengths are for air-entrained concrete. For non-air-entrained concrete mixtures, these strengths should be increased by 20%.

average measured strengths of mixtures in this study based on typical overdesign for strength. The specified RCPT values are conservatively established from the average measured values.

ACI 318-14 Exposure Class C2 applies to concrete members exposed to moisture and an external source of chlorides. Concrete mixtures used for members assigned to exposure class C2 are required to have a maximum w/cm of 0.40 and a minimum compressive strength of 5000 psi (35 MPa). In addition, there are requirements for chloride ion content and concrete cover. Based on this study, the alternative to the current w/cm and strength requirements proposed are RCPT and strength test criteria for the “Very Low” chloride penetrability (Table 6). It is recommended that RCPT be used as a basis to prequalify concrete mixtures and strength acceptance criteria be used for jobsite acceptance samples. This is similar to the current process and more performance-based. If RCPT is used as an acceptance test on jobsite samples it is important to recognize that the testing variation of this test method is two to three times greater than that for strength tests. Testing requirements should be suitably adjusted so that concrete of acceptable quality is not rejected (Obla and Lobo 2007). The RCPT and strength criteria suggested will result in mixtures with low-chloride D_a that will assure a longer service life of reinforced concrete structures exposed to external chlorides in service. For example, service life model Life-365 predicts that a concrete mixture with a w/cm of 0.40 can have a service life that varies between 15 and 56 years for a parking garage built in Baltimore, MD, depending upon the composition of the cementitious materials used. It is therefore suggested that these proposed performance-based criteria will lead to a better outcome compared to specifying the maximum w/cm requirement of 0.40. While ACI 318 covers buildings, these criteria can be used for other types of structures, such as bridges and marine structures.

CONCLUSIONS

1. Among the rapid index tests evaluated in this study, the RCPT was the best index test method in selecting mixtures based on their chloride penetrability for specimens in saturated and cyclic wet/dry conditions relative to the apparent chloride diffusion coefficient of the mixtures. However, RCPT by itself did not reliably categorize some mixtures, generally those with high w/cm in combination with higher quantities of some SCMs. A factor derived from the ratio of the RCPT and estimated pore solution conductivity of the mixture helped categorize those mixtures accurately, but that was not a good predictor for chloride penetrability when all the mixtures were considered.

2. A combination of RCPT and strength criteria is proposed as an alternative to the current w/cm and strength criteria to categorize mixtures for chloride penetrability.

3. Use of the previously described criteria can reliably be used as an alternative to prescriptive criteria such as w/cm , SCM types, and minimum quantities of cementitious materials in specifications.

4. A good correlation is observed between RCPT and conductivity test results and criteria based on ASTM C1760 can be used as an alternative to ASTM C1202.

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- **Student competitions** – participate in ACI's written and/or team-based competitions
- **Scholarships and fellowships** – students who win awards are provided up to \$10,000 and may be offered internships and paid travel to attend ACI's conventions
- **ACI Award for University Student Activities** – receive local and international recognition for your University's participation in concrete related activities
- **Free access to ACI Manual of Concrete Practice** – in conjunction with ACI's chapters, students are provided free access to the online ACI Manual of Concrete Practice
- **ACI online recorded web sessions and continuing education programs** – online learning tools ideal for use as quizzes or in-class study material