Performance-Based Specifications for Concrete Exposed to Chlorides

Alternative approaches for durability

by Kyle A. Riding, Michael D.A. Thomas, R. Doug Hooton, Karthik H. Obla, and W. Jason Weiss

Concrete producers are often required to make concrete according to the customer's recipe, even though they know that they could make concrete that can attain a better performance at a lower price. This may sometimes be the case for concrete made for buildings that will be exposed to chlorides, where the customer is compelled to use the prescriptive requirements in the ACI 318-14 Building Code.[1] Alternatives to prescriptive requirements are in the form of performance-based specifications, based on "a set of clear, measurable, and enforceable instructions"[2] that meet the owner's needs. To define those alternatives, one must examine the problems caused by chloride exposure of reinforced concrete, how chlorides get into concrete, current building code requirements, and options and criteria available for test methods that measure the concrete's resistance to chloride ingress.

Chloride-Induced Corrosion

Corrosion of reinforcing steel in concrete is the largest cause of concrete deterioration, and it results in billions of dollars of annual maintenance costs in the United States alone.[3] In new concrete, embedded reinforcing steel forms a passive oxide layer (gamma-ferric hydroxide) that protects the steel from corrosion. This passive layer remains stable in the high-pH environment of concrete. However, if the concrete around the steel carbonates and reduces the pH, or if the concrete contains a high enough level of chlorides, the passive layer will become unstable—and corrosion ensues.

Chlorides can get into fresh concrete via the mixing water, contaminated aggregate, or chemical admixtures. But much more often, water-borne chlorides are carried into the pores of hardened concrete through forced gradients in chloride concentration, moisture content, temperature, or pressure. The ease at which chloride-containing solutions can flow into concrete is often referred to as permeability[4] but, due to the different mechanisms of fluid ingress, this characteristic is better called penetrability.

Concrete's resistance to fluid penetration can be improved by reducing the volume and connectivity of the pores in the matrix, typically achieved by minimizing the water-cementitious materials ratio (w/cm) using supplementary cementitious materials (SCMs). Some SCMs such as silica fume and metakaolin effectively improve the resistance to chloride penetration at early ages, while fly ash and slag cement provide larger decreases in penetrability at later ages. Regardless of the SCM content, concrete's resistance to fluid penetration improves with greater maturity or degree of hydration.

Once chlorides enter the pores, some of them are held up (bound) by chemical reaction with, or are physically adsorbed by, cement hydration products. The total chloride content in the concrete is the sum of the bound chlorides and the chlorides in the pore solution that are free to migrate further into the concrete, termed the free chlorides. The cementitious material composition, concrete temperature, and concrete carbonation all affect the chloride binding potential of the concrete.[5] For example, metakaolin contains a high quantity of alumina and increases chloride binding, whereas silica fume slightly reduces chloride binding.[6] However, the benefits of chloride binding may not be observed in short-duration chloride exposure tests.

Current ACI 318 Requirements

ACI 318-14 Building Code attempts to increase structural life through prescriptive requirements that indirectly improve chloride penetration resistance by requiring both minimum

Table 1:
Concrete environmental categories based on chloride exposure in ACI 318-14, Table 19.3.1.1 and 19.3.2.1[1]

Chloride exposure category	Category description	Maximum *w/cm*	Minimum f'_c, psi	Maximum water-soluble chloride ion (Cl^-) content in concrete, % by weight of cement	
				Nonprestressed concrete	Prestressed concrete
C0	Concrete dry or protected from moisture	N/A	2500	1.00	0.06
C1	Concrete exposed to moisture but not to an external source of chlorides	N/A	2500	0.30	0.06
C2	Concrete exposed to moisture and an external source of chlorides from deicing chemicals, salt, brackish water, seawater, or spray from these sources	0.40	5000	0.15	0.06

Note: 1 MPa = 145 psi

concrete compressive strength f'_c and maximum *w/cm* (Table 1).[1] Many structures face additional environmental exposure requirements. For example, parking garages exposed to deicing chemicals would also be classified as a freezing-and-thawing category F3 with its associated *w/cm*, f'_c, air content, and cementitious material limits.

The limits provided in Table 1 are very indirect and somewhat ineffective methods of trying to limit chloride penetration into the concrete. Both the concrete resistance to fluid penetration and strength are related to the porosity; however, the relationship is not a linear one. Since *w/cm* is difficult to measure, a minimum compressive strength requirement was adopted as an indirect measure of the *w/cm*, an f'_c of 5000 psi (35 MPa) is commonly achieved for air-entrained concrete with a *w/cm* of 0.40. For non-air-entrained concrete or for concrete with certain SCMs, however, this relationship does not necessarily hold true. For example, a mixture with silica fume could have an f'_c of 5000 psi (35 MPa) at a *w/cm* higher than 0.40.

Alternatives

The ideal test for the concrete's ability to keep out chloride ions for corrosion protection would be one that directly measures the concrete pore system and its connectivity; includes chloride binding; accounts for the decrease in chloride penetrability with aging; and is rapid, low cost, and easy to perform. What are the options? Current alternative tests can be classified as measures of chloride ingress rates from ponding tests or from concrete electrical tests that indirectly provide a measure of the pore volume and connectivity of the pore network.

Concrete chloride exposure tests

Concrete ponding tests include ASTM C1543[7] (similar to AASHTO T 259[8]) and ASTM C1556,[9] in which a mature concrete slab or sample is exposed to a chloride solution for at least 90 or 35 days, respectively. The chloride concentration is then measured at different depths to quantify the chloride ingress rate. In ASTM C1556, the total chloride concentration with depth profile is used to determine a diffusion coefficient using Eq. (1)[9]

$$C(x,t) = C_s - (C_s - C_i) \cdot erf\left(\frac{x}{\sqrt{4 \cdot D_a \cdot t}}\right) \tag{1}$$

where $C(x,t)$ is the chloride concentration (%) at depth x (m) and time t (s); C_s is the concrete surface chloride concentration (%); C_i is the initial chloride concentration (%); and D_a is the concrete apparent diffusion coefficient (m^2/s).

D_a is referred to as the concrete apparent diffusion coefficient because it is fit to the total acid-soluble chloride concentration data. Because only the free chlorides diffuse into the concrete but D_a is fit to the total chloride concentration, the term apparent is used to signify that it is a combination of these effects. The chloride diffusion coefficient that only includes the diffusion of free chlorides and not any effects of chloride binding is termed the effective diffusion coefficient D_{eff}.

Concrete ponding tests are expensive, results differ based on the type and concentration of salt used, and they take a lot of time to complete because of the long ponding times required and because of the labor required to grind the concrete layer by layer and measure the acid-soluble chloride content with depth. These negative features limit the desirability of a ponding test as a performance test.

Electrical analog tests

Pioneering work done by Gus Archie in the 1940s and continued by other oil-field geologists and engineers developed the concept of the formation factor F to empirically describe the ability of brine to flow through rock formations.[10] This relationship states that F is a function of the total porosity of the rock, as well as the tortuosity and constriction of the pore network.[10] Archie found that the pore network connectivity, tortuosity, and degree of constriction could be measured by the electrical conductivity of the brine-saturated rock, if one accounted for the brine solution electrical conductivity. This method is based on the assumption that the electrical conductance occurs through the brine portion of the sample. High brine concentrations would give higher measured rock conductivity values. *F* normalizes for the brine conductivity to give just the effects of the pore system on fluid transport through the rock.

Like rocks, concrete is a porous material where liquid and ionic movement is of interest. *F* has been found to describe diffusion properties of concrete through the relationship given in Eq. (2)

$$F = \frac{\rho}{\rho_0} = \frac{D_i}{D_{eff}} \qquad (2)$$

where ρ is the electrical resistivity of the concrete; ρ_0 is the electrical resistivity of the concrete pore solution; and D_i is the self-diffusion coefficient for the ion of interest, equal to 2.032×10^{-9} for Cl^- at 25°C.[11]

To measure *F* in concrete and calculate D_{eff} for evaluation of the concrete's ability to keep chlorides away from the steel, one must measure the concrete electrical resistivity (or its inverse, conductivity) and the concrete pore solution electrical resistivity (or conductivity).

There are many test methods available for measuring concrete electrical properties. Even though they measure the same fundamental property, they go about it in different ways. The first standard test method to measure concrete electrical properties was the so-called rapid chloride permeability test (RCPT) method developed by Whiting[12] and standardized as AASHTO T 277[13] and later as ASTM C1202.[14] The total current passed through the sample during the 6-hour period is used to classify the concrete's fluid penetration resistance, as shown in Table 2. This test takes at least 2 days to complete (including specimen preparation and test setup) and is somewhat labor intensive.

A simplified version of the RCPT method for determination of bulk electrical conductivity of concrete has also been developed (ASTM C1760[15]). This test method is much quicker and easier to perform than ASTM C1202, and it provides results that correlate well with ASTM C1202 results.[16]

A concrete surface resistivity (SR) test method is specified for use by some departments of transportation and has been standardized as AASHTO T 358.[17] Concrete bulk resistivity (BR) testing has been standardized as a provisional standard AASHTO TP 119.[18]

A strong correlation exists between concrete RCPT, bulk conductivity, SR, and BR.[19] These tests all measure the same fundamental concrete electrical properties. As such, they are all affected similarly by factors that influence the concrete electrical properties. Changes in the concrete saturation level, temperature, pore solution composition, aggregate electrical conductivity, or conductive fibers or admixtures used can all change the measured concrete electrical properties.[20] Calculation methods to correct for temperature and saturation level have been proposed.[21] Heterogeneity in samples, especially near the surface from drying or leaching during curing, can also cause differences in results, making sample treatment important.[22]

Table 2:
Concrete chloride ion penetrability classification per ASTM C1202[14]

Charge passed, coulombs	Chloride ion penetrability
> 4000	High
2000 to 4000	Moderate
1000 to 2000	Low
100 to 1000	Very low
< 100	Negligible

Determination of the pore solution electrical resistivity (conductivity) is needed for normalization to calculate *F*. Three methods have been proposed to obtain the pore solution resistivity (conductivity), with increasing degrees of effort required and accuracy obtained.[11] Characteristics of these three methods are:

- Assume constant pore solution resistivity (conductivity) for all concretes used. This is what is currently inherently done in classification systems based solely on electrical-based test results such as those shown in Table 2;
- Use a calculator to calculate the pore solution resistivity (conductivity) based on thermodynamics modeling or other models developed to predict the pore solution composition from the raw materials used and an assumed cement degree of reaction. NIST has developed such a calculator[23] (**www.nist.gov/el/materials-and-structural-systems-division-73100/inorganic-materials-group-73103/estimation-pore**);
- The electrical resistivity (conductivity) of the pore solution is dominated in these calculators by the concentration of sodium and potassium in the pore solution. A comparison of sodium and potassium concentrations measured from pore solution pressed from hardened cement paste samples at 90 days was compared to that predicted using the NIST pore solution calculator and is shown in Fig. 1. While the calculator accounts for the pore solution composition, an error of 20% or more may be expected. Additionally, pore solution calculators do not account for all types of materials available for use in concrete; and
- Directly measure the pore solution composition through use of a sensor or a pore press to extract the pore solution from a sample. Pore solution conductivity sensors have been shown to measure the pore solution conductivity in laboratory experiments.[26] Pore solution extraction can be performed on paste, mortar, or concrete samples; however,

it is currently impractical for routine use or with mixtures having low-*w*/*cm* or highly reacted systems.

Curing greatly affects the pore solution conductivity. More markedly in low *w*/*cm* concretes, sealed samples will undergo some self-desiccation, increasing the concentration of ions in the pore solution. The overall concrete conductivity will be reduced however, because of the reduced degree of saturation.

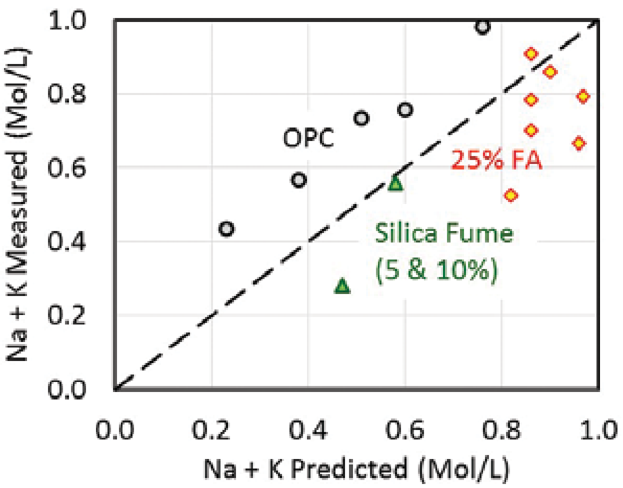

Fig. 1: Comparison of sodium and potassium concentrations in pore solution pressed from hardened cement paste samples (unpublished data) to that predicted by the NIST pore solution calculator[24,25]

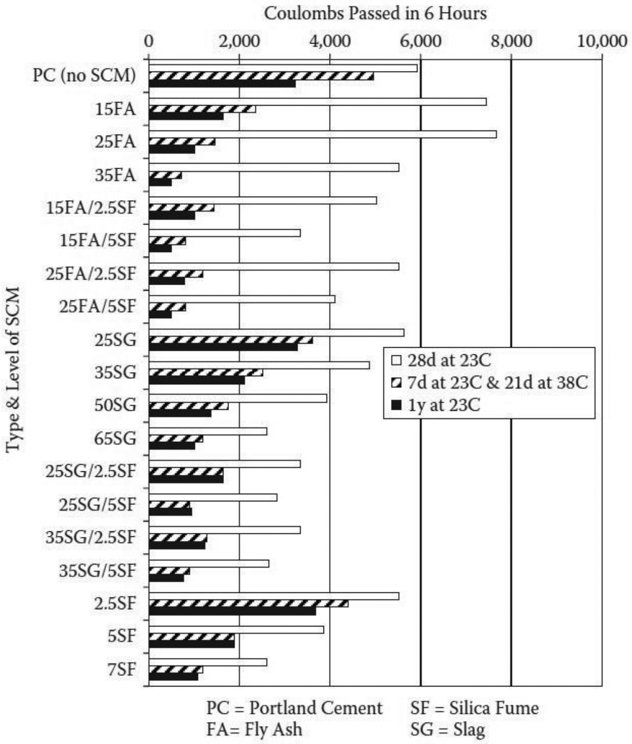

Fig. 2: Effect of curing time and temperature on charge passed per ASTM C1202, rapid chloride permeability test (RCPT) (from Reference 29 using data from Reference 30)

Sodium and potassium leaching occurs in samples cured according to ASTM C192/C192M[27] in the fog room or in lime-water baths. Work is ongoing to determine if concrete cylinders could be cured in simulated pore solutions to minimize leaching.[28] Clearly, more work is needed to determine the best method to obtain accurate measures of the pore solution resistivity (conductivity) to allow calculation of the concrete formation factor, and more work is needed to define how to cure samples prior to testing to ensure saturation and prevent leaching.

Performance Standard Options

Until the SR or BR methods are standardized in consensus standards, ASTM C1202 and C1760 are preferred for use in a performance standard for concrete exposed to chlorides per ACI 318. Additionally, until standardized methods to account for the pore solution composition are adopted, one option for considering pore solution to calculate F for use in ACI 318 would be to specify a constant pore solution resistivity (conductivity). As long as the performance option to ACI 318 provides for better concrete than what is currently required, these limitations may be acceptable until pore solution resistivity (conductivity) test methods are standardized.

The next question to answer for a performance standard is: "How should samples be cured before measurement to best represent their in-service performance?" As shown in Fig. 2, SCMs decrease the concrete penetrability more with age than concrete made without SCMs. Tests performed on concrete containing SCMs, cured according to ASTM C192/C192M in a fog room or lime-water bath at 73°F (23°C) at 28 days, may in fact show worse performance than concrete without SCMs, even though the SCMs improve penetrability in the structure. An accelerated curing method was developed[30] to increase the rate of concrete property development and pick up the effects of SCMs on penetrability. This method uses heat to accelerate the cementitious material hydration reaction and is described as an accelerated moist curing method in ASTM C1202. According to this method, the samples are moist cured under standard conditions for 7 days, after which they are placed in a lime-saturated water bath at 100 ± 3.6°F (38.0 ± 2.0°C) for 21 days before testing.

There is already widespread use of electrical test methods by North American departments of transportation and in other countries. In Canada, for example, CSA A23.1[31] provides a requirement of a maximum charge passed of 1500 coulombs by 91 days as measured by ASTM C1202 for reinforced concrete in chloride exposure (essentially the same as C2 exposure in ACI 318-14), and 1000 coulombs for concretes exposed to chlorides, where a long service life is required. A survey of departments of transportation showed that 11 U.S. states or Canadian provinces already have specifications in place for use of either ASTM C1202 or surface resistivity test limits, with additional states considering implementation.[32] Experience has shown that it is very difficult to produce a concrete that can meet these requirements without the use of SCMs.

Inclusion in the ACI 318 Code of a performance-based specification based on electrical tests would lead to the use of SCMs or blended cements to meet the requirements, thus improving the durability of concrete structures and providing contractors and material suppliers with more flexibility to innovate. In terms of how the specification should be designed, the use of a simple equation for F would allow for the use of any of the different electrical test methods currently available. This approach would allow for future test methods, and it could be done with limited complexity, as shown in Eq. (3)

$$F = \frac{\rho}{\rho_0} \tag{3}$$

In this simple equation, the pore solution resistivity ρ_0 can be assumed to be 0.1 Ω·m (unless it is measured), and ρ can be calculated from RCPT tests using Eq. (4)[33]

$$\rho = \frac{206{,}830}{Q} \tag{4}$$

where Q is the RCPT value (coulombs).

Requiring an F value of 1370 equates to requiring an RCPT value of 1500 coulombs, in line with what is required by CSA A23.1. Because the current maximum *w/cm* of 0.40 in ACI 318-14 for a C2 exposure will on average give a much higher RCPT value than 1500 coulombs, this performance-based requirement would improve the quality of currently allowed concrete.

Conclusions

One of the best and most cost-effective means of extending the service life of reinforced concrete exposed to chlorides is to use concrete with a low penetrability. This is currently indirectly achieved through prescriptive requirements in the ACI 318 Code, with its limits on the maximum *w/cm* and minimum compressive strength. Inclusion of a performance-based alternative in the Code could provide for innovation and ultimately better in-place concrete. Theory tells us that F would be the ideal specification parameter, as it is a material property that describes the concrete pore volume, tortuosity, and degree of connectivity without interference from pore solution resistivity (conductivity). F can be calculated from concrete electrical tests and the concrete pore solution electrical resistivity (conductivity). There are currently no standardized means to measure the pore solution electrical conductivity, although use of F provides the flexibility for use

of a test method once adopted in the near future.

While research is currently being performed to determine a practical method to measure or calculate the pore solution conductivity, concrete electrical tests can still provide a performance-based approach that can be adopted. Concrete that exhibits less than 1500 coulombs of charge passed in the RCPT or an equivalent conductivity value in ASTM C1760 will still provide for better protection against chloride ingress than what is currently used as a minimum requirement by the ACI 318 Code. Lastly, we recommend that specifications call for accelerated moist curing as allowed in ASTM C1202, to provide a better index of the impact of longer-term hydration of SCMs on concrete performance.

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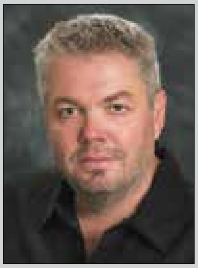
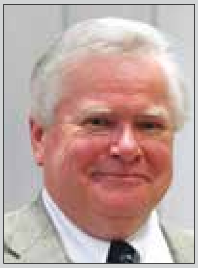
Selected for reader interest by the editors.

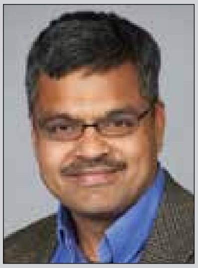
ACI member **Kyle A. Riding** is an Associate Professor of Civil and Coastal Engineering at the Engineering School of Sustainable Infrastructure and Environment at the University of Florida, Gainesville, FL. He is Secretary of ACI Committee 231, Properties of Concrete at Early Ages, and a member of ACI Committees 201, Durability of Concrete; 207, Mass and Thermally Controlled Concrete; 236, Material Science of Concrete; and S803, Faculty Network. He received his BS in civil and environmental engineering from Brigham Young University, Provo, UT, and his MSE and PhD in civil engineering from The University of Texas at Austin, Austin, TX.



Michael D.A. Thomas, FACI, is a Professor of Civil Engineering at the University of New Brunswick, Fredericton, NB, Canada. He is a member of the *ACI Materials Journal* Editorial Board; ACI Committees 201, Durability of Concrete; 221, Aggregates; 232, Fly Ash in Concrete; 233, Ground Slag in Concrete; 234, Silica Fume in Concrete; 236, Material Science of Concrete; 239, Ultra-High Performance Concrete; 240, Pozzolans; 308, Curing Concrete; 365, Service Life Prediction; S803, Faculty Network; and ACI Subcommittee 130-A, Materials. He is also a member of CSA technical committees A23.1/A23.2 and A3000. He received his BSc in civil engineering from the University of Nottingham, Nottingham, UK, and his PhD in civil engineering from the University of Aston, Birmingham, UK.



R. Douglas Hooton, FACI, is a Professor and NSERC/Cement Association of Canada, Senior Industrial Research Chair in Concrete Durability and Sustainability in the Department of Civil Engineering at the University of Toronto, Toronto, ON, Canada, where he has taught for more than 30 years. He serves on the ACI Board of Direction and is Chair of ACI Committee 201, Durability, and ACI Subcommittee 130-A, Materials; and a member of several other ACI Committees. He is also a RILEM Fellow and Chair of the RILEM Educational Activities Committee and a member of several RILEM technical committees.



Karthik H. Obla, FACI, is Vice President of Technical Services at the National Ready Mixed Concrete Association (NRMCA), Silver Spring, MD. He serves on several ACI committees, including ACI Committee 201, Durability of Concrete; and 329, Performance Criteria for Ready Mixed Concrete. He is a recipient of ACI's Young Member Award for Professional Achievement and served as President of the San Antonio Chapter – ACI. He received his BS in civil engineering from IIT (BHU), Varanasi, India, and his MS and PhD in civil engineering from the University of Michigan, Ann Arbor, MI.

W. Jason Weiss, FACI, is the Miles Lowell and Margaret Watt Edwards Distinguished Chair in Engineering and Head of the School of Civil and Construction Engineering at Oregon State University, Corvallis, OR. He is Chair of the *ACI Materials Journal* Editorial Board and ACI Committee 231, Properties of Concrete at Early Ages. He is also a member of the ACI Board Committee Chairs Committee; ACI Committees 201, Durability of Concrete; 213, Lightweight Aggregate and Concrete; 236, Material Science of Concrete; 318, Structural Concrete Building Code; S803, Faculty Network; and ACI Subcommittee 318-A, General, Concrete, and Construction. He received his BAE in architectural engineering from Pennsylvania State University, State College, PA, and his MS and PhD in civil engineering from Northwestern University, Evanston, IL.