

# Testing Transport Properties in Concrete

Assessing key indicators of durability

BY D. STEPHEN LANE, RACHEL J. DETWILER, AND R. DOUGLAS HOOTON

Limiting the ingress of water and aggressive ions such as chlorides is fundamental for the durability of concrete structures. The most significant factors are water-cementitious material ratio ( $w/cm$ ), appropriate use of supplementary cementitious materials (SCMs), and unit water content. Concrete mixtures should be evaluated using test methods that bear some relation to the anticipated exposure conditions. In this article—which is based on two articles featured in *HPC Bridge Views*<sup>1,2</sup> and a chapter that will be included in the next revision of ACI 201.2R—some of the current standard test methods for evaluating transport properties in concrete are discussed.

## CHLORIDE PENETRATION TESTS

### Ponding

**AASHTO T259 and ASTM C1543:** These test methods simulate the mechanisms by which chloride ions penetrate into concrete bridge decks. The test specimens generally consist of concrete slabs with a minimum thickness of 75 mm (3 in.). The area of the top surface of the slab is required to be at least 0.03 m<sup>2</sup> (46.5 in.<sup>2</sup>), but larger specimens are commonly used. A dike is constructed around the perimeter of the top surface, allowing ponding of an aggressive solution on the specimen. The slabs are typically moist cured and then dried at 50% relative humidity (RH) before ponding with a 3% sodium chloride (NaCl) solution. AASHTO T259 calls for moist curing for 14 days, followed by drying for 28 days. ASTM C1543 allows for a good deal of flexibility in curing.

Prior to ponding, the sides of ASTM C1543 slabs are sealed to prevent evaporation from those surfaces and to impose one-directional control of the chloride penetration. (AASHTO T259 makes no provision for sealing the sides.) The ponded slabs are stored to allow air circulation around the bottoms in a room at about 50% RH, allowing evaporation from the bottoms of the slabs. A cover is placed over the solution pond to prevent evaporation of water from the solution. AASHTO T259 calls for a ponding period of 90 days. For low-permeability concretes, this is typically too short for significant penetration of chloride ions into the concrete, and ponding is often extended. For this reason, ASTM C1543 allows the investigator to select the ponding period based on the materials under test, recommending initial sampling at 90 days with subsequent sampling at 6 and 12 months and at 12-month intervals thereafter.

At the end of the exposure period, the excess solution and salt buildup are removed. In AASHTO T259, the slab is sampled in 1/2 in. (12.5 mm) thick horizons taken at two or three depths. These are analyzed for chloride ion content relative to a baseline value determined on a companion concrete specimen that was not exposed to external chlorides. This test can also be conducted using a different salt or concentration in the ponding solution. It should be noted, however, that the type of cation(s) in the ponding solution affects the rate of ingress of chloride ions. For example, penetration of the chlorides would be faster with a potassium chloride (KCl) solution than with a NaCl solution.

While some investigators have adopted an integrated or average chloride content value for ranking chloride penetration resistance,<sup>3</sup> it has been shown that this isn't

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a reliable approach,<sup>4</sup> as the depth of penetration of chloride ions is the dominant factor affecting the corrosion of reinforcing bars, not the total chloride content.

Although the ponding test does provide a crude one-dimensional profile of chloride ion ingress, the profile is not a reflection of chloride diffusion alone. The initial mode of ingress of the ions is by absorption of water and chlorides into the dried concrete, especially for concretes containing SCMs.<sup>5</sup> The exposure of the bottom face to a 50% RH environment during the test induces evaporation, meaning that chloride ions can also migrate by wicking.<sup>6</sup> Finally, diffusion of the chlorides also takes place. McGrath and Hooton<sup>4</sup> observed that, while all three of these mechanisms do occur in bridge decks, the test exaggerates the importance of the sorption component.

For high-quality concretes, it can be difficult to develop a chloride profile based on a 90-day ponding period because so little chloride penetrates into the concrete beyond initial absorption. The precision of

the sampling can make a significant difference in the conclusions that can be drawn from the results. In analyzing their data from AASHTO T259 tests, McGrath and Hooton<sup>4</sup> showed that taking 1/2 in. (12.5 mm) thick samples makes it difficult to distinguish between a high-quality concrete, in which there is a high concentration of chlorides near the surface, and a low-quality concrete, in which the chlorides penetrate much farther in. Extending the ponding period to 180 days and increasing the number of samples taken help resolve this problem.<sup>3,4,7,8</sup>

### Immersion

**ASTM C1556:** This test method avoids some of the problems associated with ASTM C1543 in that the concrete specimens, typically cast cylinders or cores, are sealed on all but one surface and kept saturated with a calcium hydroxide solution before exposure to a NaCl solution. The specimens are then placed in a concentrated (165 g/L) NaCl solution for at least 35 days, and the chloride ions enter the specimen only by diffusion,

## TRANSPORT MECHANISMS

Water and ions migrate into and within concrete by different mechanisms. The common test methods used to measure liquid and ion transport in concrete generally bring more than one mechanism into play, and not always in the same proportions in different types of concrete. To sort them out, it helps to have some basic definitions:

**Absorption**—the process by which a liquid is drawn into and tends to fill permeable pores in a porous solid body; also, the increase in mass of a porous solid body resulting from the penetration of a liquid into its permeable pores (as defined in ASTM C125).

**Apparent chloride diffusion coefficient,  $D_a$** —a chloride transport parameter calculated from acid-soluble chloride profile data obtained from saturated specimens exposed to chloride solutions, without correction for chloride binding, that provides an indication of the ease of chloride penetration into cementitious mixtures (as defined in ASTM C1556).

**Chloride binding**—the chemical process by which a chloride ion is removed from a solution and incorporated into cementitious binder hydration products (as defined in ASTM C1556).

**Diffusion**—the movement of dissolved ions from areas of higher concentration or potential to areas of lower concentration or potential, or the movement of vapor from areas of higher pressure to lower pressure.

**Diffusivity, effective**—the rate of movement of a particular ion species within the pore solution in a porous medium.

**Migration**—movement of ions through a porous medium due to a difference in electrical potential; a means sometimes used to accelerate chloride testing and calculation of diffusion coefficients.

**Permeability**—the property of a porous medium that characterizes its resistance to flow of a liquid under a pressure gradient.

**Permeation**—the flow of a liquid through a porous medium under a pressure gradient.

**Pore solution**—the liquid within the voids in a porous medium.

**Porous medium**—a solid material with interconnected voids that allow movement of fluids.

**Sorptivity**—a measure of the rate of absorption of a liquid into an unsaturated porous medium by capillarity.

**Transport, advective**—the movement of ions via bulk solution flow or absorption through a porous medium.

**Transport, capillary**—movement of a liquid through a porous medium driven by tension on the pore solution created by the solution's affinity for the medium.

**Wicking**—the capillary transport of a liquid through a porous medium to an exposed surface where the liquid evaporates and any dissolved ions are precipitated as salts in the pores or on the surface of the medium.

not by sorption or wicking. Longer exposure times are recommended for mature concretes, concretes with low  $w/cm$ , or high-performance concretes containing SCMs. The exposure time can be extended. Due to time-dependent effects—primarily the continued hydration of the cementitious materials—the length of the exposure period will affect the measured results, so comparative tests of concretes should be performed for the same period of exposure.<sup>9</sup>

The sampling is more precise than for AASHTO T259. A nominal 4 in. (100 mm) diameter core from the slab is mounted in a mill or lathe and a series of thin layers (each about 1 mm [0.039 in.] thick) are ground off (Fig. 1). The powder from each layer is collected separately and analyzed for acid-soluble chloride content. The apparent diffusion coefficient is determined using nonlinear regression analysis to fit the data to a numeric solution to Fick's Second Law.

The use of Fick's Second Law to reduce the data from ponding tests is a convenient but questionable practice. Petterson<sup>10</sup> noted that the applicability of Fick's Second Law, which is a simplification of a more general equation describing ion transport, depends on the validity of three assumptions:

- The material in which diffusion takes place is permeable and homogeneous;
- The diffusion properties of the material do not change with time or with the concentration of the diffusing ion; and
- No chemical reaction or physical binding of the diffusing ion occurs.

Petterson<sup>10</sup> noted that all three of these assumptions are violated in the diffusion of chloride ions through concrete. That is, concrete is heterogeneous, its diffusion properties change with time and with the concentration of the diffusing ion, and both chemical reactions and physical binding can occur. ASTM C1556 uses the term "apparent chloride diffusion coefficient" to make clear that the result obtained is not a true diffusion coefficient. However, to determine time-dependent changes in apparent diffusion, ASTM C1556 tests can be conducted on concretes at different ages.<sup>9</sup> Chloride binding tests for different cementitious binders can also be performed separately to correct the apparent diffusion values in service life models.

## Electrical

**AASHTO T277 and ASTM C1202:** Because of the duration of ponding tests, Whiting<sup>11</sup> developed what has come to be known as the rapid chloride permeability (RCP) test or "coulomb" test. This test is standardized as AASHTO T277 and ASTM C1202. Under a 60-volt DC potential, the current passing through the water-saturated concrete is measured and integrated over a 6-hour period

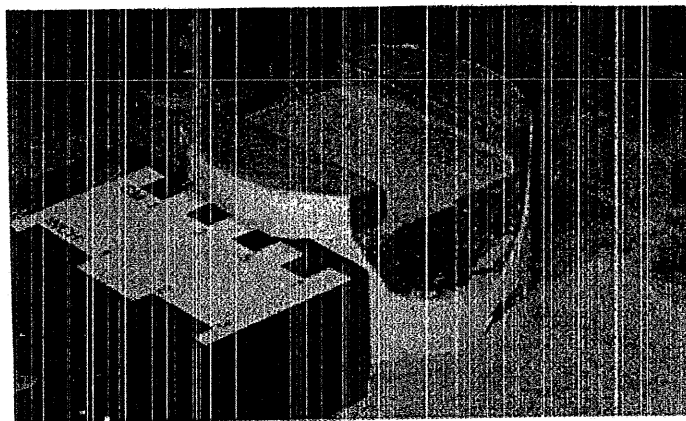


Fig. 1: Milling ASTM C1556 specimen in 1 mm (0.039 in.) layers for chloride content (photo courtesy of R.D. Hooton)

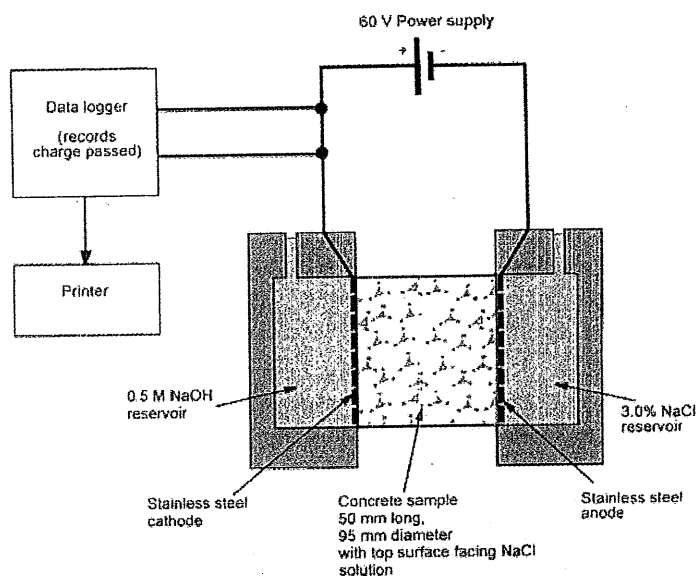


Fig. 2: Schematic of ASTM C1202 test setup<sup>31</sup> (1 mm = 0.039 in.)

to obtain the charge passed in coulombs. The nominal 4 in. (100 mm) diameter, 2 in. (50 mm) thick specimens are placed between two cells, one containing a 0.3N sodium hydroxide (NaOH) solution, the other containing a 3% NaCl solution, each cell containing an electrode (Fig. 2). The total charge passed during the 6-hour test is an indirect indication of the chloride ion penetrability of the concrete. Values are adjusted for the area of the actual specimen tested relative to the area of the standard 3.75 in. (95 mm) diameter specimen.

Essentially, ASTM C1202 uses the electrical conductivity (the inverse of resistivity) of the concrete and its pore solution as a surrogate or index for diffusivity. This is generally reasonable, as resistance to both electrical and ionic movement will be affected by the porosity and pore connectivity of the concrete. Although the main objection to the use of this test stems from the indirect nature of the measurement, there are additional, related concerns:

- Electrical resistance over the 6-hour test period is affected by the Joule effect (ohmic heating)<sup>12-14</sup> and pore solution chemistry<sup>15</sup>; and
- Different proportions of SCMs can affect the pore solution chemistry. For example, Page and Vennesland<sup>16</sup> found that 10% silica fume (by substitution) reduced the concentrations of  $\text{Na}^+$ ,  $\text{K}^+$ , and  $\text{Ca}^{2+}$  by about 50% and that of  $\text{OH}^-$  by about 75% in the pore solution.

The effects of SCMs on electrical resistance are not completely understood. Detwiler and Fapohunda<sup>17</sup> compared the results of AASHTO T277 to those found by directly measuring chloride ion migration for portland cement concretes with and without slag cement and found that AASHTO T277 unduly favored the concretes containing SCMs. They attributed the differences between the two sets of test results to differences in pore solution chemistry. However, Nokken and Hooton<sup>18</sup> found that the effects of pore solution chemistry on bulk conductivity measurements were a only a secondary effect, and Hooton et al.<sup>19</sup> showed that the relative effects of silica fume on concrete transport properties were similar, regardless of whether ASTM C1202, C1543, or C1556 was used.

Corrosion inhibitors such as calcium nitrite add ions to the pore solution, dramatically increasing the charge passed. There is some evidence that calcium nitrite increases the penetrability of the concrete matrix, meaning that increased coulomb values may be partly due to microstructural effects as well as to changes in the pore solution chemistry.<sup>20,21</sup> If ASTM C1202 is used in qualifying concrete mixtures for use in construction, the concrete will typically be tested without the corrosion inhibitor to qualify it and then with the corrosion inhibitor to provide a baseline value for quality control purposes. The latter measurement will be considerably higher.

The relationship between electrical conductivity and chloride penetration can also vary with the modes of transport involved. Diffusion through voids and cracks differs from diffusion through undamaged concrete; thus, the presence of flaws in the concrete can significantly affect the results of the test.<sup>22</sup>

Low-quality concrete is difficult to evaluate properly using ASTM C1202 because the temperature of the specimens rises when the current is applied (Joule effect), increasing the rate of diffusion. McGrath and Hooton<sup>4</sup> proposed a modification to reduce these effects. The ASTM C09.66 Subcommittee is close to completing a

new test method based on ASTM C1202 but with a duration of 5 minutes to eliminate the heating effect and expressing the results as a conductivity or resistivity value. (Simpler bulk resistivity measurements are also being developed.) High-quality concretes can be difficult to distinguish from one another because the total charge passed is so low and because there is variability in the test results.<sup>23</sup> While ASTM C1202 has also been criticized for its harsh testing conditions,<sup>12,24-26</sup> the method is rapid and convenient. It generally relates to other measures of resistance to fluid transport<sup>23,27</sup>; and if properly interpreted, it can be used effectively for quality control in construction. (This has been formalized in the 2010 revision of ASTM C1202).

Table 1 provides example performance limits based on the RCP test using an accelerated curing protocol of 7 days standard moist curing followed by 21 days immersed in lime-saturated water at 100°F (38°C) to encourage the use of SCMs while maintaining a 28-day limit.<sup>23</sup> Alternatively, some agencies specify maximum values at 56 or 90 days under standard curing conditions to provide sufficient time for property development. At later ages, it's also reasonable to specify somewhat lower maximum values. In Canada, for reinforced concrete exposed to chlorides (Exposure Class C-1), CSA A23.1-09 specifies a maximum average of 1500 coulombs at 56 days of age with no single value to exceed 1750 coulombs.

**AASHTO TP64:** This test method is a rapid migration test procedure based on Nordtest NT Build 492, which operates under the same principle as the RCP test but is designed to drive chloride ions into the concrete specimen so that their depth of penetration can be measured. Test specimens have the same dimensions as the RCP test. The test apparatus is fairly simple. The concrete specimen is sealed in a neoprene sleeve and placed on an electrode immersed in NaCl solution in a tub. The second electrode is placed in the sleeve immersed in NaOH solution. The potential across the specimen is set based on its initial conductivity and then maintained for the 18-hour period.

Alternatively, the RCP test apparatus can be used. Major differences between the two methods are that a higher (10% versus 3%) concentration NaCl solution is used in the rapid migration test; the voltage across the electrodes is decreased with increasing initial conductivity; and the test duration is 18 hours rather than 6 hours. Following the test, the specimen is split in half and sprayed with silver nitrate solution to provide a visual indication of the depth of chloride penetration (Fig. 3). The test results correlate well with ponding tests (Fig. 4).<sup>29,30</sup>

**TABLE 1:**  
**VIRGINIA DOT CRITERIA FOR LOW-PERMEABILITY CONCRETES**  
**USING AASHTO T277**

Concrete class	Maximum value charge passed at 28 days, coulombs
Prestressed concrete and other special designs (for example, low-permeability overlays)	1500
Reinforced concrete (for example, bridge elements)	2500
Paving	3500

Note: Specimens are subjected to accelerated curing.

## ABSORPTION TESTS

### Bulk

**ASTM C642:** One test for the absorption of water by hardened concrete is ASTM C642, in which a piece of



concrete at least 350 mL (21 in.<sup>3</sup>) in volume is oven dried to constant mass and then immersed in water until it again reaches constant mass. The specimen is then boiled for 5 hours, allowed to cool, and the mass determined again. The absorption of water after immersion and after immersion and boiling is determined. It should be noted that the initial oven drying likely induces cracking in the specimen, thus increasing the measured absorption.

### Rate

**ASTM C1585:** This method is used to measure the water sorptivity (rate of absorption) into a concrete surface, which is often of greater interest than bulk absorption. The specimens are typically 4 in. (100 mm) diameter, 2 in. (50 mm) long slices of cylinders. Specimens are conditioned and then allowed to

equilibrate to a presumed stable internal RH of 80%. The target RH of 80% was chosen because most of the capillary pores should be empty. The specimens are initially stored at 122°F (50°C) for 3 days at 80% RH, then sealed in individual containers and stored at 73°F (23°C) for 2 weeks to allow the internal RH of the specimens to come to equilibrium. The sides of the specimens are then sealed with tape and the faces of the specimens opposite the absorbing surface are covered to reduce evaporation. The specimens are then weighed, and the one exposed face is placed in water (Fig. 5).

At increasing time intervals, the specimens are removed from the water, their surfaces blotted to remove excess surface water, and reweighed. Frequent measurements are made during the first 6 hours of testing, followed by daily measurements for at least 8 days. The

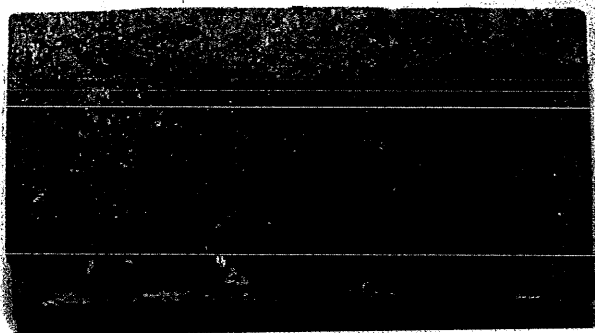


Fig. 3: Photo of split sample after spraying with silver nitrate solution in AASHTO TP64 rapid migration test. The white layer has reacted with chloride ions to form silver chloride (photo courtesy of R.D. Hooton)

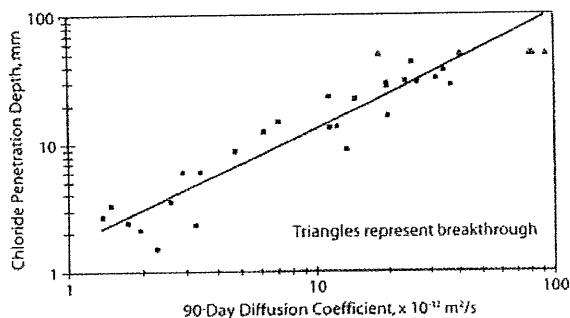


Fig. 4: Relation between chloride penetration in AASHTO TP64 (vertical axis) and ASTM C1556 apparent chloride diffusion values. As noted by triangles, in some cases the chlorides penetrated the full 50 mm (2 in.) thickness of the rapid migration test specimen<sup>31</sup>

# What the Concrete Industry Knows About SUSTAINABILITY

Sustainable concrete should have a life cycle of well over 100 years, perhaps 150. That will be achieved by having a minimum of shrinkage and cracking, high concrete density, high mortar strength, low permeability, dense and homogenous interfacial transition zone (ITZ), low long term carbonation resulting in reinforcing steel being un-blemished, and a wearing surface that does not degrade. For structural design of concrete, there should be predictable modulus of elasticity and a high early age and later age flexural and compressive strength. Construction should be trouble free during mixing, placing, and finishing of the concrete, and flat surfaces should be free of cracks and have a wearing surface that resists deterioration from traffic or applied chemicals. Concrete in place should have a minimum of warping.

To achieve optimum concrete characteristics, many designers are concluding that low water-cement (w/c) ratio is the ratio of choice to reduce drying shrinkage, cracking, and excessive permeability, and to increase the flexural and compressive strength through early age (<3d) and later age (>90d) hydration of the cement (c) and supplementary cementitious materials (SCM). One existing, presently available, method to accomplish the desired results is through the use of high performance concrete (HPC), using internal curing (IC), with high volume fly ash (HVFA) or slag cement.

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**TABLE 2:**  
SORPTIVITY AND APPARENT DIFFUSION COEFFICIENTS FOR SELECTED CONCRETES<sup>31</sup>

Concrete w/cm		100% portland cement			6% silica fume
		C1	C2	C3	C4
		0.58	0.48	0.38	0.38
ASTM C1585	Initial rate, mm/s $\times 10^{-4}$	6.2	23.5	8.7	4.8
ASTM C1585	Secondary rate, mm/s $\times 10^{-4}$	15.8	11.2	6.5	2.3
ASTM C1556	Apparent diffusion coefficient, m <sup>2</sup> /s $\times 10^{-12}$	10.6	10.2	7.5	1.9

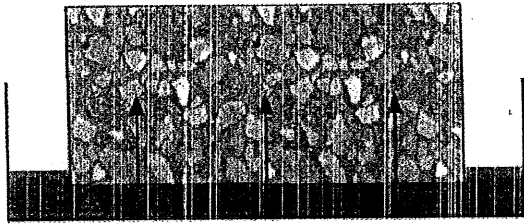


Fig. 5: Schematic of ASTM C1585 sorptivity test setup

change in mass over time is used to calculate the higher initial sorptivity over the first 6 hours and the secondary rate over the succeeding days. These are expressed as initial and secondary rates, respectively.

Acceptable limits on the permeability for durability have not yet been determined but would vary depending on the exposure conditions and performance requirements.

Table 2 contains sorptivity values and apparent chloride diffusion coefficients for four concretes reported by Lane.<sup>31</sup> Concretes C1, C2, and C3 were portland cement concretes, whereas Concrete C4 contained 6% silica fume as a portion of the cementitious material.

## SUMMARY

There are a number of ASTM and AASHTO test methods for evaluating the resistance of concrete to ingress of liquids. They measure liquid penetration by different mechanisms and need to be selected based on anticipated exposure conditions. Some tests are lengthy to perform and are suited only for research or prequalification testing. For quality assurance purposes during construction, electrical conductivity tests are good indicators of concrete's resistance to fluid penetration; but until additional improved standard tests become available, rapid index tests, such as ASTM C1202 or AASHTO TP 64, are the most useful.

## References

References for this article can be found with the electronic version available at [www.concreteinternational.com](http://www.concreteinternational.com).

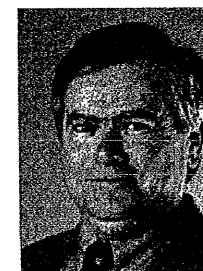
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